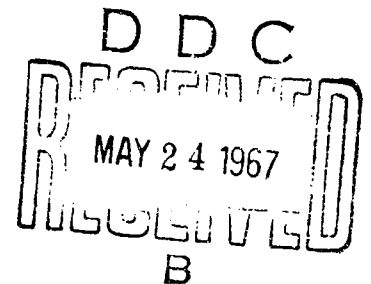AD651946

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AN INVESTIGATION OF THE THRUST AUGMENTATION CHARACTERISTICS OF JET EJECTORS

By

K. P. Huang

E. Kisielowski

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U. S. ARMY AVIATION MATERIEL LABORATORIES FORT EUSTIS, VIRGINIA

216

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This report has been reviewed by the US Army Aviation Materiel
Laboratories and is considered to be technically sound.

The work was performed under Contract DA 44-177-AMC-322(T) in
order to determine the capabilities and limitations of the jet
ejector as a thrust augmentor. As a result of this program a
rapid method for jet ejector performance prediction was
formulated and is herein offered as a tool for the designer.

AN INVESTIGATION OF THE
THRUST AUGMENTATION CHARACTERISTICS
OF JET EJECTORS

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K. P. Huang
E. Kisielowski

Prepared by

Dynasciences Corporation
Blue Bell, Pennsylvania

for

SUMMARY

Presented in this investigation is a theoretical analysis of
the thrust augmentation characteristics of jet ejectors.
The analysis includes the effects of flow compressibility,
major flow losses, and forward speed. Numerical results are
presented in the form of nomographs for a wide range of
practical operating conditions. These computations were
performed with the aid of an IBM 360 digital computer. The
charts can be used to predict the jet ejector performance
and as such represent an effective analytical tool for
preliminary design purposes. The numerical results are used
to determine the effects of the more important aerodynamic,
thermodynamic, and geometric parameters on jet ejector
thrust augmentation. A correlation of these results with the
available experimental data is also made.

FOREWORD

This report presents analyses and numerical evaluations of
the thrust augmentation characteristics of jet ejectors.
The work was sponsored by the U. S. Army Aviation Materiel
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performed by the Dynasciences Corporation, Blue Bell,
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Mr. Roy Burrows was the Army technical representative. His
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The following Dynasciences Corporation personnel authored
or contributed to this report:

Mr. K. P. Huang - Project Engineer
Mr. E. Kisielowski - Manager, Aerodynamics
Mr. T. Estes - Aerodynamicist
Mr. T. Fukushima - Senior Aeronautical Engineer
Mr. J. Tang - Aeronautical Engineer

CONTENTS

ILLUSTRATIONS

xi

SYMBOLS

A	cross-sectional area, square feet
a	radius of the primary jet, feet
C_c	compressibility correction factor ϕ_c/ϕ_I
c_p	specific heat at constant pressure, British thermal units per pound per degree Rankine
D	diameter of the mixing chamber, feet
d	diameter of the nozzle, feet
F	thrust, pounds
f	friction factor
g	acceleration of gravity, 32.17 feet per second squared
H	total head, pounds per square foot
h	correction for ρ_{Ip} in the Newton-Raphson iterative procedure
i	an index number
J	mechanical equivalent of heat, 778.2 foot-pounds per British thermal unit
K_I, K_2	programmed constants for the initial conditions in the iteration procedure
k	correction for V_2 in the Newton-Raphson iterative procedure
L	length of the mixing chamber, feet
M	Mach number

m	mass flow rate, pounds per second
N	number of nozzles
P	pressure, pounds per square foot
R	gas constant, British thermal units per pound per degree Rankine
r	jet boundary distance from the jet axis, feet
r'	radial distance from jet center line nondimensionalized by the jet radius
S	contact area, square feet
T	temperature, degrees Rankine
V	velocity, feet per second
V_α	forward speed of the jet ejector system parallel to the ejector axis, feet per second
w	entrainment ratio (mass flow ratio)
X	distance from the jet exit along the ejector-axis, feet
α_E	secondary-to-primary area ratio
α_D	diffuser exit-to-entrance area ratio
γ	specific heat ratio
ϵ	iteration convergence criteria
η	thermal efficiency factor
η_M	mixing efficiency
θ	primary jet expansion angle, degrees

κ a parameter defining nonuniform velocity profile at the secondary entrance

λ_D diffuser loss factor defined as

$$\lambda_D = \frac{H_2 - H_3}{\dfrac{\rho V_2^2}{2g}\left(1 - \dfrac{1}{\alpha_D}\right)^2}$$

λ_E secondary entrance loss factor defined as

$$\lambda_E = \frac{H_a - H_{l_s}}{\dfrac{\rho V_{l_s}^2}{2g}}$$

μ ratio of the forward speed to the velocity of the jet exhausted directly to the ambient

ξ an integral defined by equation (110)

ρ density, pounds per cubic foot

ϕ thrust augmentation ratio

χ empirical correction factor for thrust augmentation ratio due to nonuniform velocity profile at the secondary entrance

ψ_1, ψ_2 denote equations (154) and (155) , respectively

SUBSCRIPTS

A   annular

a   denotes the ambient conditions

C	compressibility
D	diffuser
E	entrance
I	ideal
L	losses
M	multiple
o	denotes the stagnation conditions
p	pertains to the primary flow
s	single
s	pertains to the secondary flow
1	denotes Station 1, i.e., the plane at the exit of the primary nozzle, which is also the plane at the entrance to the mixing chamber
2	denotes Station 2, i.e., the plane at the exit of the mixing chamber, which is also the plane at the entrance to the diffuser
3	denotes Station 3, i.e., the plane at the exit of the diffuser

NOTE: Symbols with bars denote uniform values in the one-dimensional idealized analysis.

I. INTRODUCTION

The concept of generating thrust augmentation by means of a
jet ejector became an active research subject several
decades ago. Since then, numerous studies have been
conducted providing a considerable amount of jet ejector
data. Much of this work was done, however, for different
and diverse applications, and because of the complexity of
the jet ejector flow problems, the available information
cannot be readily used for practical applications to aircraft
design and performance.

The main objective of this program is to evaluate the avail-
able data as to their practical applicability and to extend
and modify existing theories to provide an analysis for
realistic appraisal of the potential of jet ejectors for
achieving augmented thrust.

The review of the existing literature covered a major
portion of technical reports (total 585) which are listed
in Appendix II. A discussion of the more important of these
investigations is presented in Section III.

The theoretical analyses which are formulated in Section IV
are performed for an axisymmetric ejector and include the
effects of compressibility, flow losses, and ejector geom-
etry. These analyses utilize various simplifying assumptions,
among which are the conditions that the velocity profile at
the secondary entrance is uniform and that the mixing of the
primary and secondary flows is completed at the exit of the
mixing chamber. The former assumption limits the appli-
cability of this one-dimensional theoretical approach to
not too large secondary-to-primary area ratios. A three-
dimensional analysis is indeed a formidable task and has not
been undertaken by any of the investigators in the past. To
keep the complexity of the analysis within the scope of the
present program, an empirical correction factor for thrust
augmentation ratio is herein formulated to account for the
effect of the nonuniform velocity distribution at the
secondary entrance. The latter assumption implies that the
mixing chamber length of a given ejector configuration must
be sufficiently long to ensure complete mixing of the exit
flows. No precise information is available on this subject,
and therefore a semiempirical approach is herein utilized

1

for qualitative evaluation of the mixing chamber length required for complete mixing.

Furthermore, a comprehensive parametric study is conducted to determine the effects of the more important aerodynamic, thermodynamic, and geometric parameters on jet ejector performance. A discussion of these effects is presented in Section V.

Section VI contains a correlation of the theoretical results with the available experimental data.

Section VII contains a summary of the theoretical results for rapid predictions of jet ejector performance. These results were obtained with the aid of an IBM 360 digital computer and are presented as nomographs.

II. JET EJECTOR PRINCIPLE

A jet ejector is a device in which a secondary, or driven,
fluid is entrained by a primary or actuating fluid with
subsequent transfer of energy through turbulent mixing in a
mixing chamber. The primary fluid, which is originally at a
higher stagnation pressure, is discharged with a high
velocity into the mixing chamber of specific shape. Due to
viscous shear, the fluid surrounding the primary flow is
brought into motion at the entrance of the mixing chamber.
This motion causes a drop of static pressure, as a result of
which the secondary fluid, in many cases ambient air, is
entrained into the mixing chamber. The secondary flow thus
formed mixes turbulently with the primary jet in the mixing
chamber and energy transfer occurs. The mixed flow then
proceeds toward the exit end of the mixing chamber and
finally discharges to some back pressure which may be
atmospheric. If a diffuser is attached, the mixed flow
builds up some static pressure before reaching the exit. As
a result of the pumping action as described above, the total
momentum of the mixed flow at the ejector exit is increased
due to the entrainment of the secondary fluid, as compared
with the momentum of the primary jet discharged directly into
the atmosphere. Jet thrust augmentation is thus achieved.

In essence, the jet ejector can be considered as a device
which converts a low mass flow propelled at high velocity to
a high mass flow propelled at low velocity. If this is
accomplished at little energy loss, thrust augmentation can
be achieved.

The efficiency of this conversion process depends on the
ejector configuration, the detail geometry of these configu-
rations, and the thermodynamic and aerodynamic operating
conditions.

The more important jet ejector configurations are as follows:

    (a)   Single nozzle ejector

    (b)   Multiple nozzle ejector

    (c)   Annular nozzle ejector

The prime parameter affecting the performance of these configurations is the minimum mixing chamber length required for complete mixing of the primary and the secondary flows. No precise analytical methods are available for determining this parameter; therefore, a semiempirical method is herein formulated for this purpose. An analysis of various ejector types is presented in Section IV.

The major geometric parameters affecting thrust augmentation are:

  (a) Secondary-to-primary area ratio at the entrance to the mixing chamber.

  (b) Shape and length of the mixing chamber.

  (c) Diffuser exit-to-entrance area ratio and diffuser angle.

  (d) Primary nozzle configuration and location.

  (e) Secondary entrance inlet contour.

Finally, the thermodynamic and aerodynamic parameters of importance are:

  (a) Stagnation properties of the primary fluid.

  (b) Stagnation properties of the secondary fluid.

  (c) Atmospheric conditions at the ejector exit.

  (d) Forward speed of the ejector system.

III.   REVIEW OF THE AVAILABLE PERTINENT LITERATURE

Presented in this section is a brief review of the state of
the art of jet ejectors. The papers selected for this
discussion are those which are more directly related to the
work under the present program, and they are herein arranged
in a chronological order. A more complete bibliography on
jet ejectors is presented in Appendix II.

The analysis performed by Roy (Reference 1) deals with
compressible fluid flow under practical operating conditions
of jet ejectors. Entrance and diffuser losses are accounted
for by assuming the flow processes as polytropic. The
friction loss at the mixing chamber wall is also considered.
This analysis results in a system of 24 flow equations for
which no close-form or digital computer solutions are
presented.

Morrisson (Reference 2) performs an incompressible analysis
in which it is assumed that the mass flow rate of the
primary jet exhausted to the ambient is the same as that
discharged into the mixing chamber. This assumption may not
be valid since the pressure reduction created in the mixing
chamber results in an increase of mass flow rate of the
primary jet as compared to that when the primary jet is
discharged into the atmosphere. The analysis presents
charts of thrust augmentation ratio versus the mass flow
ratio. However, these charts cannot readily be applied for
determining jet ejector performance, since the mass flow
rate is unknown.

Sargent (References 3 and 4) performs idealized analyses of
the performance of jet ejectors for both static and forward
speed conditions. In these analyses, the flows are assumed
to be incompressible and the solution for the flow equations
is made by a trial and error method with the area ratio and
mass flow ratio as variables. These analyses rely on the
assumption that the mass flow rate of the primary jet
exhausted to the ambient is equal to that of the primary jet
inside the ejector.

The analysis of McClintock et al (Reference 5) results in an
equation for thrust augmentation as a function of the mass
flow ratio which is not determined. In spite of the fact

5

that the analysis is performed for incompressible fluids, an attempt is made to account for different densities of primary and secondary flows. This appears to be contradictory, since an incompressible analysis is only valid for primary and secondary fluids of nearly equal densities.

Ellerbrock's analysis (Reference 6), which includes the loss due to wall friction, treats compressible flow for constant area mixing. However, in obtaining solutions to the flow equations, assumed values of the pressure ratio at the ejector entrance plane to that of the ambient are introduced.

The analysis performed by von Kármán (Reference 7) presents the basic information on cylindrical jet ejectors operating under idealized, incompressible flow conditions. The expression for the nondimensionalized velocity of the mixed flow at the exit appears to be erroneous, although the relationship for thrust augmentation ratio finally obtained is correct. In this analysis, an attempt is made to account for the effect of the nonuniform velocity profile at the secondary entrance on jet ejector thrust augmentation. However, the analysis utilizes the assumption that the mass flow rate for the nonuniform velocity profile is the same as that in the case of uniform velocity distribution. As the result of this assumption, an increase rather than a reduction in thrust augmentation is achieved.

Szczeniowski, in his incompressible analysis (Reference 8), considers a hypothetical approach in which momentum and energy are transferred between the primary and secondary streams while the two flows remain separate at the exit of the ejector. The justification of this approach is rather difficult.

Sanders et al (Reference 9) compute the ejector thrust by integration of surface pressures; however, the momentum of the flow from the exit of the ejector is completely ignored. This approach does not yield the total thrust augmentation.

The analysis performed by Bertin et al (Reference 10) utilizes the usual one-dimensional flow approach but yields no close-form solution for the jet ejector performance. The

performance charts presented in this reference have limited
practical application because the mass flow ratio which is
used as an independent variable cannot be determined.

Chisholm's work (Reference 11) covers compressible and
incompressible flows with constant area and constant pressure
mixing. Although the ejector flow equations are formulated,
no solution has been attempted for determining the thrust
augmentation ratio.

Reid's investigation (Reference 12) is chiefly aimed at the
reduction of jet noise by means of an ejector; however, an
expression of a so-called thrust parameter is presented. A
simplified theoretical analysis for constant   mixing with
assumed common stagnation temperature for the primary and
secondary streams is presented. The analysis indicates that
although the system of flow equations formulated can be
solved in principle, the numerical solutions are very
difficult to obtain.

The analysis presented in Reference 13 is for a constant
pressure mixing jet ejector with diffuser. The primary and
secondary flows are assumed to have the same stagnation
temperature. As pointed out in this reference, the system
of equations can be solved when the mixing pressure is known.
However, since the mixing pressure is one of the parameters
to be determined, this analysis has no direct practical
application.

Storkebaum in his work (Reference 14) deals with both
incompressible and compressible flow analyses. For the
incompressible case, the idealized thrust augmentation ratio
is presented as a function of the secondary-to-primary area
ratio. The effect of the losses at the entrance to the
mixing chamber is also studied. In the compressible analysis,
the equations for thrust augmentation are formulated;
however, the procedure of solving the equations is not
presented.

Wan performs an incompressible analysis (Reference 15)
similar to that presented by von Kármán (reference 7), with
the exception that the mixed flow velocity at the ejector

7

exit is considered to be nonuniform. However, the validity of this analysis appears to be doubtful because, despite the nonuniformity of the exit velocity, the static pressure at the exit is assumed to be uniform.

Payne (Reference 16) conducts a theoretical analysis of a jet ejector with constant pressure mixing treating flows as incompressible. This analysis indicates that the optimum thrust augmentation is primarily dependent on the diffuser efficiency and that augmentation ratios as high as 4.0 or more are possible with high diffuser efficiencies. This conclusion is based on an infinite secondary-to-primary mass flow ratio which cannot be achieved in practice. Also, in performing the differentiation process to obtain optimum thrust augmentation, the analysis uses the pressure in the mixing chamber as the independent variable and considers the mass flow ratio as a constant. This appears to be incorrect, since the mass flow ratio appearing in the basic flow equation is a function of the pressure in the mixing chamber and cannot be treated as a constant. Furthermore, in the breakdown of the location of thrust increase, the analysis indicates that the largest contribution to the total thrust augmentation is due to the bellmouth lip intake rather than the change of momentum of incoming and outgoing flows. No experimental data are presented to justify this conclusion.

Sandover (Reference 17), utilizing the work of Payne (References 16 and 18), performs an analysis also based on one-dimensional incompressible fluid flow. This analysis commences with an assumption that the constant pressure in the mixing chamber can be achieved with a uniform cross section of the chamber; then an attempt is made to determine the optimum exit-to-entrance area ratio. Furthermore, the analysis indicates that an increase in thrust augmentation can be achieved by increasing the temperature of the primary jet flow. This is considered to be incorrect for both the incompressible or compressible flow analyses. In the former case, temperature does not affect the thrust; in the latter case, as indicated in the present report, the increase of the primary jet temperature results in a decrease ratner than an increase of the thrust augmentation ratio. This result has been verified by available experimental data.

From the above review, it is seen that little usable information on jet ejector performance is available in the existing technical literature. Despite the fact that in numerous investigations, equations representing the ejector flows are formulated, no explicit solutions are presented for the practical evaluation of jet ejector performance. In the cases where some numerical solutions are presented, they are generally expressed as functions of such parameters as the mass flow ratio, the pressure at the mixing chamber entrance, primary jet Mach number, etc., none of which can be readily determined.

IV. THEORETICAL ANALYSES

As pointed out in the previous section, the presently
available literature does not provide adequate information
on the thrust augmentation characteristics of jet ejectors.
Existing analyses were therefore modified and extended and
practical methods were formulated by means of which the
potential of jet ejectors can be effectively evaluated.

Because of the complexity of the problem, the following
simplifying assumptions are made:

(a) The ejector geometry is axisymmetrical.

(b) The velocity and static pressure of the primary
     and secondary flow are uniform at the entrance
     plane to the mixing chamber.

(c) The static pressures of the primary and secondary
     flows at the entrance to the mixing chamber are
     equal.

(d) The velocity and static pressure of the mixed flow
     are uniform at the exit of the mixing chamber, and
     in the case of an ejector with diffuser are
     uniform for any cross section of the diffuser.

(e) Both the primary and secondary fluids are perfect
     gases having the same specific heat.

(f) The pressure at the exit of the mixing chamber, or
     in the case of a diffuser, at the exit of the
     diffuser, is equal to the ambient pressure.

(g) The stagnation conditions of the primary flow are
     unaffected by the presence of the ejector, and the
     losses in the primary flow up to the exit of the
     nozzle are neglected.

(h) No heat losses occur at the mixing chamber and
     diffuser walls.

(i) The motion of the ejector system, if any, is in
     the same direction as that of the primary jet flow.

With these simplifying assumptions, the ejector flow field is
reduced to a one-dimensional fluid flow problem which can be
treated analytically utilizing the following principles of
fluid dynamics:

  (a) Conservation of mass.

  (b) Conservation of energy.

  (c) Newton's second law.

  (d) Equation of state for perfect gases.

  (e) Thermodynamic processes of the flows.

The formulation of the jet ejector flow equations is herein
accomplished utilizing Figure 1. As indicated in this
figure, various stations of jet ejectors are designated by
numbers (0), (1), (2), and (3) which are assigned to
represent the respective stations of the jet ejector flows
as follows:

  Station (0) Upstream of the entrance of the mixing
               chamber.

  Station (1) Plane at the entrance of the mixing
               chamber, which is also the exit plane
               of the primary nozzle.

  Station (2) Plane at the exit of the mixing chamber,
               which is also the plane at the entrance
               of the diffuser.

  Station (3) Plane at the exit of the diffuser.

Utilizing the nomenclature of Figure 1 and the assumptions
and conditions described above, the following jet ejector
flow equations are obtained:

11

⓪ ① ② ③

P_a
ρ_a
T_a
V_α

P_{op}
T_{op}

$P_1, \rho_{1s}, T_{1s}, V_{1s}$

$P_1, \rho_{1p}, T_{1p}, V_{1p}$

P_2, ρ_2, T_2, V_2

P_a, ρ_3, T_3, V_3

Mixing Chamber   Diffuser

➡ Primary Flow

⇨ Secondary Flow

➡ Mixed Flow
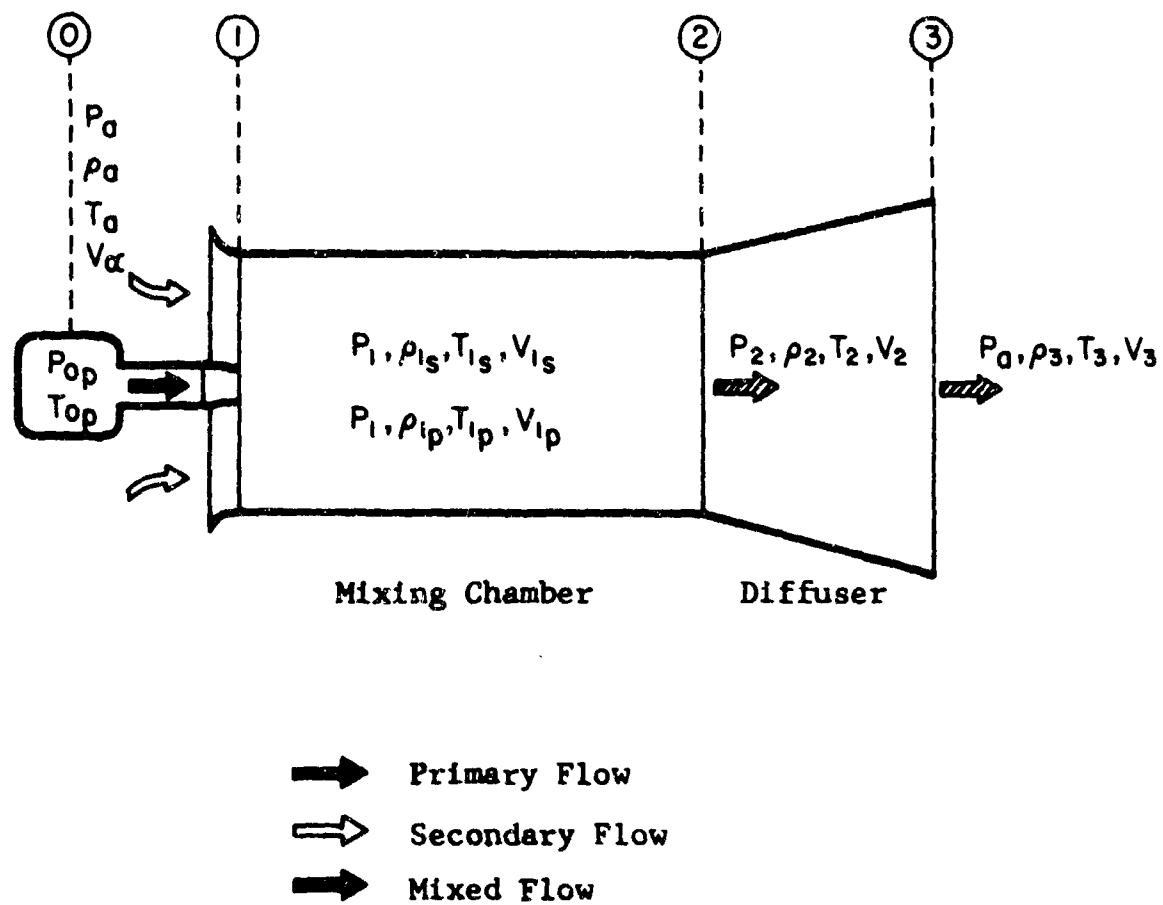
Figure 1. Schematic Representation
of Jet Ejector Configuration.

Continuity in the Mixing Chamber

$$\rho_{l_p} V_{l_p} + \alpha_E \, \rho_{l_s} V_{l_s} = (\alpha_E + 1) \rho_2 V_2 \tag{1}$$

Continuity in the Diffuser

$$\rho_2 V_2 = \alpha_D \rho_3 V_3 \tag{2}$$

Momentum Across the Mixing Chamber

$$(\alpha_E + 1)(P_2 - P_1) = \frac{\rho_{l_p} V_{l_p}^2}{g} + \frac{\alpha_E \rho_{l_p} V_{l_s}^2}{g} - \frac{(\alpha_E + 1)\rho_2 V_2^2}{g} -$$

$$\frac{(\alpha_E + 1) f (L/D)(\rho_{l_s} + \rho_2)(V_{l_s} + V_2)^2}{4g} \tag{3}$$

Conservation of Energy in the Mixing Chamber

$$\rho_{l_p} V_{l_p} c_p T_{0_p} J + \alpha_E \rho_{l_s} V_{l_s} c_p T_a J + \frac{V_a^2}{2g})$$

$$= (\alpha_E + 1)\rho_2 V_2 \left(\frac{\gamma}{\gamma - 1} \cdot \frac{P_2}{\rho_2} + \frac{V_2^2}{2g} \right) \tag{4}$$

Conservation of Energy in the Diffuser

$$\frac{\gamma}{\gamma - 1} \cdot \frac{P_2}{\rho_2} + \frac{V_2^2}{2g} = \frac{\gamma}{\gamma - 1} \cdot \frac{P_a}{\rho_3} + \frac{V_3^2}{2g} \tag{5}$$

13

Conservation of Energy for the Primary Flow up to the Nozzle Exit

$$c_p \, T_{0_p} \, J = \frac{\gamma}{\gamma - 1} \cdot \frac{P_1}{\rho_{1_p}} + \frac{V_{1_p}^2}{2g} \tag{6}$$

Conservation of Energy for the Secondary Flow up to the Entrance to the Mixing Chamber

$$c_p \, T_a \, J + \frac{V_\alpha^2}{2g} = \frac{\gamma}{\gamma - 1} \cdot \frac{P_1}{\rho_{1_s}} + \frac{V_{1_s}^2}{2g} \tag{7}$$

Isentropic Process of the Primary Flow

$$\frac{P_1}{P_{0_p}} = \left(\frac{\gamma}{\gamma - 1} \cdot \frac{P_1}{\rho_{1_p} c_p T_{0_p} J} \right)^{\frac{\gamma}{\gamma - 1}} \tag{8}$$

Irreversible Adiabatic Process for the Secondary Flow up to the Entrance to the Mixing Chamber

$$\frac{P_1}{P_a} = \left[\frac{1}{\eta_E} \cdot \frac{\gamma}{\gamma - 1} \cdot \frac{P_1}{\rho_{1_s} c_p T_a J} + \left(1 - \frac{1}{\eta_E} \right)\left(1 - \frac{V_\alpha^2}{2g \, c_p T_a J} \right) \right]^{\frac{\gamma}{\gamma - 1}} \tag{9}$$

Irreversible Adiabatic Process in the Diffuser

$$\frac{P_2}{P_a} = \left[\frac{\rho_2 \left(\frac{\gamma}{\gamma - 1} \cdot \frac{P_2}{\rho_2} + \eta_D \frac{V_2^2}{2g} \right)}{\rho_3 \left(\frac{\gamma}{\gamma - 1} \cdot \frac{P_2}{\rho_2} + \frac{V_2^2}{2g} \right)} \right]^{\gamma} \tag{10}$$

14

The unknown quantities in the above equations are: P_1, P_2, V_{1p}, V_{1s}, V_2, V_3, ρ_{1p}, ρ_{1s}, P_2, and P_3. The problem basically reduces to a simultaneous solution of 10 nonlinear equations with 10 unknowns. As can be noted, no close-form solution for these equations is possible, and even an iterative solution with the aid of a digital computer is indeed a formidable task.

Hence, in order to obtain a practical evaluation of jet ejector performance, further simplifications are necessary in the analysis.

The present approach consists of first formulating a very simplified analysis, defined herein as the idealized analysis, which enables rapid prediction of maximum thrust augmentation and the entrainment ratio of jet ejectors, for the most idealized flow conditions. The idealized analysis is herein formulated considering perfect fluid flow with no losses and no forward speed effects. This analysis is performed for two types of jet ejectors with constant area mixing and constant pressure mixing.

As a second step, a practical analysis is formulated. This analysis consists of two parts:

(a) The effects of major flow losses, forward speed, and diffuser are considered assuming incompressible fluid flow.

(b) The effect of flow compressibility is determined on the basis of no flow losses, no diffuser, and no forward speed.

This approach makes it possible to perform with reasonable computational effort a comprehensive parametric study of the relative importance of the individual flow parameters on jet ejector performance and also provides a practical method for the evaluation of various jet ejector systems.

A. IDEALIZED ANALYSIS

The idealized analysis, which in part is also presented in Reference 7, utilizes the following additional simplifying assumptions:

15

(a) The flows are incompressible, which implies that the fluid density is uniform and constant throughout for all the flows and is unaffected by temperature and pressure.

(b) All flow losses are neglected.

(c) The ejector system has no forward speed.

These assumptions apply to both constant area mixing and constant pressure mixing.

1. Constant Area Mixing

The thrust augmentation ratio ϕ is defined as the ratio of the thrust produced with an ejector on F_3 to that produced by the primary jet when it is discharged directly into the atmosphere F_{a_p}.

Thus,

$$\phi = \frac{F_3}{F_{a_p}} \tag{11}$$

where the thrust produced by the ejector is given by

$$F_3 = \frac{\rho}{g} A_3 V_3^2 \tag{12}$$

and the thrust produced by the primary jet discharged directly into the atmosphere is

$$F_{a_p} = \frac{\rho}{g} A_{1_p} V_{a_p}^2 \tag{13}$$

16

Substituting equations (12) and (13) into equation (11), there follows

$$\phi = \frac{A_3 V_3^2}{A_{1p} V_{ap}^2}$$ (14)

Applying Bernoulli's equation for the primary flow discharged into the atmosphere and the primary flow discharged into the ejector, and assuming that the stagnation pressure P_{0p} is not affected by the presence of the ejector, there results

$$P_{0p} = P_a + \frac{1}{2g} \rho V_{ap}^2 = P_{1p} + \frac{1}{2g} \rho V_{1p}^2$$ (15)

Also applying Bernoulli's equation between stations (0) and (1) for the secondary flow,

$$P_a = P_{1s} + \frac{1}{2g} \rho V_{1s}^2$$ (16)

From equations (15) and (16) there results

$$P_{1s} + \frac{1}{2g} \rho V_{1s}^2 + \frac{1}{2g} \rho V_{ap}^2 = P_{1p} + \frac{1}{2g} \rho V_{1p}^2$$ (17)

Using the assumption that $P_{1p} = P_{1s}$, equation (17) reduces to

$$V_{ap}^2 = V_{1p}^2 - V_{1s}^2$$

17

or

$$\left(\frac{V_{0p}}{V_{1p}}\right)^2 = 1 - \left(-\frac{V_{1S}}{V_{1p}}\right)^2 \qquad (18)$$

Substituting equation (18) into (14) yields

$$\phi = \frac{\left(\frac{A_3}{A_{1p}}\right)\left(\frac{V_3}{V_{1p}}\right)^2}{1 - \left(\frac{V_{1S}}{V_{1p}}\right)^2} \qquad (19)$$

The analysis will now proceed to develop the relationships for V_{1S}/V_{1p} and V_3/V_{1p} in terms of the area ratios $\alpha_E = A_{1S}/A_{1p}$ and $\alpha_0 = A_3/A_2 = A_3/(A_{1p} + A_{1S})$

Using the continuity equation between stations (1) and (3), there results

$$A_{1p}V_{1p} + A_{1S}V_{1S} = A_3 V_3 \qquad (20)$$

Equation (20) reduces to

$$\frac{V_{1S}}{V_{1p}} = \frac{(\alpha_E + 1)\alpha_0\left(\frac{V_3}{V_{1p}}\right) - 1}{\alpha_E} \qquad (21)$$

Applying Bernoulli's equation between stations (2) and (3), using $P_3 \quad P_0$, there follows

$$P_2 + \frac{1}{2g}\rho V_2^2 = P_0 + \frac{1}{2g}\rho V_3^2 \qquad (22)$$

18

Substituting equation (16) into equation (22) yields

$$P_2 = P_{1s} + \frac{1}{2g}\rho V_{1s}^2 + \frac{1}{2g}\rho V_3^2 - \frac{1}{2g}\rho V_2^2 \qquad (23)$$

Also, from momentum considerations between stations (1) and (2), there results

$$A_{1p} P_{1p} + A_{1s} P_{1s} - A_2 P_2 = \frac{\rho}{g} A_2 V_2 - \frac{\rho}{g} A_{1p} V_{1p}^2 - \frac{\rho}{g} A_{1s} V_{1s}^2 \qquad (24)$$

Substituting equation (23) into (24) and using $P_{1p} = P_{1s}$ yields

$$(A_{1p} + A_{1s})P_{1s} - A_2(P_{1s} + \frac{1}{2g}\rho V_{1s}^2 + \frac{1}{2g}\rho V_3^2 - \frac{1}{2g}\rho V_2^2) = \frac{\rho}{g}A_2 V_2^2 - \frac{\rho}{g}A_{1p}V_{1p}^2 - \frac{\rho}{g}A_{1s}V_{1s}^2$$

$$\dots (25)$$

Equation (25) can be simplified as follows

$$\left(\frac{V_{1s}}{V_{1p}}\right)^2 = \frac{(a_E + 1)\left[\left(\frac{V_2}{V_{1p}}\right)^2 + \left(\frac{V_3}{V_{1p}}\right)^2\right] - 2}{a_E - 1} \qquad (26)$$

From continuity equation between stations (2) and (3),

$$V_2 = a_0 V_3 \qquad (27)$$

Squaring equation (27) and substituting into equation (26) yields

$$\left(\frac{V_{1s}}{V_{1p}}\right)^2 = \frac{(a_E + 1)(a_0^2 + 1)\left(\frac{V_3}{V_{1p}}\right)^2 - 2}{a_E - 1} \qquad (28)$$

19

Squaring equation (21) and equating it to equation (28), there results the following quadratic equation for V_3/V_{1p} :

$$\left(\frac{V_3}{V_{1p}}\right)^2 - \frac{2(\alpha_E-1)\alpha_D}{\alpha_E^2+\alpha_D^2}\left(\frac{V_3}{V_{1p}}\right) - \frac{2\alpha_E-1}{\alpha_E^2+\alpha_D^2} = 0 \tag{29}$$

Solving equation (29), the relationship for V_3/V_{1p} is as follows:

$$\left(\frac{V_3}{V_{1p}}\right) = \frac{-(\alpha_E-1)\alpha_D \pm \alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}}{\alpha_E^2+\alpha_D^2} \tag{30}$$

It can be noted that the velocity ratio V_3/V_{1p} must always be greater than zero for all positive values of the area ratios α_E and α_D. Since $\alpha_D \geq 1$, there follows that for $\alpha_E \geq 0$, the positive sign in front of the second terms must be used. Hence,

$$\left(\frac{V_3}{V_{1p}}\right) = \frac{-(\alpha_E-1)\alpha_D + \alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}}{\alpha_E^2+\alpha_D^2} \tag{31}$$

Substituting equation (31) into equation (21) yields

$$\left(\frac{V_{1s}}{V_{1p}}\right) = \frac{(\alpha_E+1)\alpha_D\left[-(\alpha_E-1)\alpha_D+\alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}\right]-(\alpha_E^2+\alpha_D^2)}{\alpha_E(\alpha_E^2+\alpha_D^2)} \tag{32}$$

Finally, substituting equations (31) and (32) into equation (19), the thrust augmentation ratio ϕ can be analytically expressed as follows:

$$\phi = \frac{\alpha_E^2(\alpha_E+1)\alpha_D\left[-(\alpha_E-1)\alpha_D+\alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}\right]^2}{\alpha_E^2(\alpha_E^2+\alpha_D^2)^2-\left\{(\alpha_E+1)\alpha_D\left[-(\alpha_E-1)\alpha_D+\alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}\right]-(\alpha_E^2+\alpha_D^2)\right\}^2}$$
$$\dots(33)$$

Similarly, the mass entrainment ratio w is given by

$$W = \alpha_E\left(\frac{V_{I_S}}{V_{I_p}}\right) = \frac{(\alpha_E+1)\,\alpha_D\left[-(\alpha_E-1)\alpha_D+\alpha_E\sqrt{\alpha_D^2+2\alpha_E-1}\right]-(\alpha_E^2+\alpha_D^2)}{\alpha_E^2+\alpha_D^2} \qquad (34)$$

For a special case of constant area mixing condition with no diffuser, i.e., $\alpha_D = 1.0$, the thrust augmentation ratio ϕ reduces to

$$\phi = \frac{(\alpha_E+1)\left[-(\alpha_E-1)+\alpha_E\sqrt{2\alpha_E}\right]^2}{(\alpha_E^2+1)^2-\left[-2\alpha_E+(\alpha_E+1)\sqrt{2\alpha_E}\right]^2} \qquad (35)$$

and the mass entrainment ratio becomes

$$W = \frac{(\alpha_E-1)\left[-(\alpha_E-1)+\alpha_E\sqrt{2\alpha_E}\right]-(\alpha_E^2+1)}{\alpha_E^2+1} \qquad (36)$$

It can be seen from equation (35) that ϕ approaches a limit of 2.0 as α_E tends to infinity. This obviously is not true even under idealized conditions, since an ejector with infinite secondary-to-primary area ratio is equivalent to a free jet discharged into the atmosphere, in which case no thrust augmentation exists and hence $\phi = 1.0$. This discrepancy is attributed to the unrealistic assumption that the secondary velocity at the entrance to the mixing chamber is uniform regardless of the area ratio. A discussion on this subject, together with the derivation of an empirical correction factor for the nonuniform secondary entrance velocity profile, is presented later in this report.

2. Constant Pressure Mixing

The mixing chamber of an ejector is sometimes of variable cross-sectional area. Due to the lack of information on the longitudinal pressure variation inside the mixing chamber, it is, in general, difficult to express the pressure force on the walls in the momentum equation. However, one configuration exists for which an analysis can easily be

21

performed. This is the so-called constant pressure mixing
configuration which implies that the pressure inside the
mixing chamber is considered constant throughout.

Thus, for constant pressure mixing, the additional condition
is that the stagnation pressur s P_{1_p} , P_{1_S} , and P_2 are equal
and can be denoted as P.

Furthermore, since the contour of the mixing chamber in this
case varies such as to maintain the constant pressure
requirement, the area at the exit of the mixing chamber A_2
cannot be equated to A_{1_p} + A_{1_S} , but must be determined from
the analysis.

It should be noted that if the flow from the mixing chamber
is directly discharged into the atmosphere, the pressure
throughout the ejector would be atmospheric. In such a case,
there would be no secondary flow entrainment and, therefore,
no thrust augmentation, i.e., ϕ = 1.0. It therefore follows
that a diffuser is required to create a pressure drop in the
mixing chamber which would entrain secondary flow in order
to produce thrust augmentation (ϕ > 1.0).

The idealized analysis for constant pressure mixing can be
performed in a manner similar to that for constant area
mixing. Thus, using equation (19), the relationship for
thrust augmentation ratio ϕ can be rewritten in the following
form:

$$\phi = \frac{\left(\dfrac{A_3}{A_2}\right)\left(\dfrac{A_2}{A_{1S}}\right)\left(\dfrac{A_{1S}}{A_{1p}}\right)\left(\dfrac{V_3}{V_{1p}}\right)^2}{1-\left(\dfrac{V_{1S}}{V_{1p}}\right)^2}$$

$$= \frac{\alpha_E\,\alpha_D\left(\dfrac{A_2}{A_{1p}}\right)\left(\dfrac{V_3}{V_{1p}}\right)^2}{1-\left(\dfrac{V_{1S}}{V_{1p}}\right)^2} \tag{37}$$

22

In order to obtain the solution for the thrust augmentation ratio for constant pressure mixing, it is now necessary to determine the area ratio A_2/A_{I_s} as well as the velocity ratios V_3/V_{I_p} and V_{I_s}/V_{I_p} . This can be accomplished as follows:

Using the continuity equation between stations (1) and (2), there results

$$A_{I_p}V_{I_p} + A_{I_s}V_{I_s} = A_2 V_2 \qquad (38)$$

Also, applying momentum considerations between stations (1) and (2) and considering the constant pressure condition at the mixing chamber walls, there follows

$$PA_{I_p} + PA_{I_s} - PA_2 - \int_{(1)}^{(2)} PdA_n = \frac{\rho A_2 V_2^2}{g} - \frac{\rho A_{I_p}V_{I_p}^2}{g} - \frac{\rho A_{I_s}V_{I_s}^2}{g} \qquad (39)$$

where dA_n is the axial component of the incremental ejector surface area.

The integral $\int_{(1)}^{(2)} PdA_n$ is given by

$$\int_{(1)}^{(2)} PdA_n = P(A_{I_p} + A_{I_s} - A_2) \qquad (40)$$

Substituting equation (40) into (39), there results

$$A_{I_p}V_{I_p}^2 + A_{I_s}V_{I_s}^2 = A_2 V_2^2 \qquad (41)$$

23

Squaring equation (38) and dividing by equation (41) yields

$$A_2 = \frac{(A_{1p}V_{1p} + A_{1s}V_{1s})^2}{A_{1p}V_{1p}^2 + A_{1s}V_{1s}^2} \tag{42}$$

Equation (42) can be transformed as follows:

$$\left(\frac{A_2}{A_{1s}}\right) = \frac{\left[\frac{1}{\alpha_E} + \left(\frac{V_{1s}}{V_{1p}}\right)\right]^2}{\frac{1}{\alpha_E} + \left(\frac{V_{1s}}{V_{1p}}\right)^2} \tag{43}$$

Using equation (20), the velocity ratio V_{1s}/V_{1p} can be expressed as follows:

$$\left(\frac{V_{1s}}{V_{1p}}\right) = \alpha_0 \left(\frac{A_2}{A_{1s}}\right)\left(\frac{V_3}{V_{1p}}\right) - \frac{1}{\alpha_E} \tag{44}$$

Substituting equation (43) into equation (44) and solving for V_3/V_{1p}, there follows

$$\left(\frac{V_3}{V_{1p}}\right) = \frac{\frac{1}{\alpha_E} + \left(\frac{V_{1s}}{V_{1p}}\right)^2}{\alpha_0 \left[\frac{1}{\alpha_E} + \left(\frac{V_{1s}}{V_{1p}}\right)\right]} \tag{45}$$

Also, from equations (23) and (27) and the constant pressure condition, there results

$$\left(\frac{V_3}{V_{1p}}\right) = \frac{1}{\sqrt{\alpha_0^2 - 1}}\left(\frac{V_{1s}}{V_{1p}}\right) \tag{46}$$

24

Equating equations (45) and (46) and simplifying, the following quadratic equation for V_{I_S}/V_{I_p} is obtained:

$$\left(\frac{V_{I_S}}{V_{I_p}}\right)^2 + \frac{\alpha_D}{\alpha_E(\alpha_D - \sqrt{\alpha_D^2 - 1})}\left(\frac{V_{I_S}}{V_{I_p}}\right) - \frac{\sqrt{\alpha_D^2 - 1}}{\alpha_E(\alpha_D - \sqrt{\alpha_D^2 - 1})} = 0 \qquad (47)$$

Solving equation (47) for V_{I_S}/V_{I_p}, there results

$$\left(\frac{V_{I_S}}{V_{I_p}}\right) = \frac{-\alpha_D \pm \sqrt{\alpha_D^2 + 4\alpha_E\sqrt{\alpha_D^2 - 1}(\alpha_D - \sqrt{\alpha_D^2 - 1})}}{2\alpha_E(\alpha_D - \sqrt{\alpha_D^2 - 1})} \qquad (48)$$

It can be noted that the velocity ratio V_{I_S}/V_{I_p} must be greater than zero. Since in equation (48) the term

$$\sqrt{\alpha_D^2 + 4\alpha_E\sqrt{\alpha_D^2 - 1}(\alpha_D - \sqrt{\alpha_D^2 - 1})} > \alpha_D$$

for $\alpha_D > 1.0$ and $\alpha_E > 0$, the velocity ratio V_{I_S}/V_{I_p} will be greater than zero only if the positive sign in front of the square root term is used. Hence,

$$\left(\frac{V_{I_S}}{V_{I_p}}\right) = \frac{-\alpha_D + \sqrt{\alpha_D^2 + 4\alpha_E\sqrt{\alpha_D^2 - 1}(\alpha_D - \sqrt{\alpha_D^2 - 1})}}{2\alpha_E(\alpha_D - \sqrt{\alpha_D^2 - 1})} \qquad (49)$$

Finally, substituting equations (43) and (46) into equation (37), the thrust augmentation ratio ϕ for constant pressure mixing can be expressed as a function of area ratios α_E and α_D and the velocity ratio V_{I_S}/V_{I_p}. Thus,

$$\phi = \frac{\alpha_D\left(\frac{V_{I_S}}{V_{I_p}}\right)^2\left[1 + \alpha_E\left(\frac{V_{I_S}}{V_{I_p}}\right)\right]^2}{(\alpha_D^2 - 1)\left[1 - \left(\frac{V_{I_S}}{V_{I_p}}\right)^2\right]\left[1 + \alpha_E\left(\frac{V_{I_S}}{V_{I_p}}\right)^2\right]} \qquad (50)$$

25

where V_{I_S}/V_{I_p} , as given in equation (49), is also a function of the area ratios α_E and α_D only.

Similarly, the mass entrainment ratio w can be expressed as

$$W = \alpha_E \left(\frac{V_{I_S}}{V_{I_p}}\right) = \frac{-\alpha_D + \sqrt{\alpha_D^2 + 4\alpha_E \sqrt{\alpha_D^2 - 1}(\alpha_D - \sqrt{\alpha_D^2 - 1})}}{2(\alpha_D - \sqrt{\alpha_D^2 - 1})} \qquad (51)$$

For the special case of constant pressure mix $\;$; ejector without diffuser, i.e., $\alpha_D = 1.0$, it is evident from equation (49) that $V_{I_S}/V_{I_p} = 0$.

The above result indicates that for the case of no diffuser, i.e., $\alpha_D = 1.0$, there will be no secondary flow and, therefore, no thrust augmentation.

B. PRACTICAL ANALYSIS

Presented in this section is a practical analysis which includes the effects of many important jet ejector flow parameters neglected in the idealized approach yet yields solutions with a relatively reasonable computational effort. This analysis pertains to a jet ejector with constant area mixing having a conical diffuser attached to the exit of the mixing chamber.

As mentioned previously, the practical analysis is performed in the following stages:

1. The Incompressible Analysis With Flow Losses

Although this analysis is based on the incompressible fluid flow conditions, it includes the following practical operating conditions and flow losses:

(a) Effect of forward speed (parallel to ejector walls).

(b) Effect of diffuser.

26

(c) The total head loss at the secondary entrance to the mixing chamber.

(d) The friction head loss at the mixing chamber walls.

(e) Total head loss in the diffuser.

For the incompressible analysis including the flow losses and the operating conditions specified above, the jet ejector flow equations (1) through (10) can be reduced to the following:

Continuity in the Mixing Chamber

$$V_{1_p} + \alpha_E V_{1_s} = (\alpha_E + 1)V_2 \tag{52}$$

Continuity in the Diffuser

$$V_2 = \alpha_D V_3 \tag{53}$$

Momentum Across the Mixing Chamber

$$(\alpha_E + 1)(P_2 - P_1) = \frac{\rho V_{1_p}^2}{g} + \frac{\alpha_E \rho V_{1_s}^2}{g} -$$
$$\frac{(\alpha_E + 1)\rho V_2^2}{g} - \frac{(\alpha_E + 1) f(L/D)\rho(V_{1_s} + V_2)^2}{2g} \tag{54}$$

Bernoulli's Equation for the Secondary Flow up to the Entrance to the Mixing Chamber

$$P_0 + \frac{\rho V \alpha^2}{2g} = P_1 + \frac{\rho(1+\lambda_E)V_{1_s}^2}{2g} \tag{55}$$

27

Bernoulli's Equation for the Flow in the Diffuser

$$P_2 + \frac{\rho\left[(\alpha_D^2-1) - \lambda_D(\alpha_D-1)^2\right]V_3^2}{2g} = P_a \qquad (56)$$

The solution of the system of five equations, (52) through (56), is similar to that presented above for the idealized theoretical analysis. In the final analysis, the five equations can be reduced to one quadratic equation for the nondimensional mixed flow velocity at the exit of the diffuser V_3/V_{1p}. This equation is

$$\left\{(\alpha_E^2+\alpha_D^2)+\mu^2\left[\alpha_E^2(\alpha_D^2-1)+2\alpha_E\alpha_D^2\right]+ \right.$$

$$\left[\lambda_E(\alpha_E+1)^2\alpha_D^2+f(L/D)(2\alpha_E+1)^2\alpha_D^2+\lambda_D\alpha_E^2(\alpha_D-1)^2\right]-$$

$$\left. \mu^2\left[f(L/D)(2\alpha_E+1)^2\alpha_D^2+\lambda_D\alpha_E^2(\alpha_D^2-1)\right]\right\}\left(\frac{V_3}{V_{1p}}\right)^2+$$

$$\left\{2(\alpha_E-1)\alpha_D-4\mu^2\alpha_E\alpha_D-2\left[f(L/D)(2\alpha_E+1)\alpha_D+\lambda_E(\alpha_E+1)\alpha_D^2\right]+\right.$$

$$\left. 2\mu^2 f(L/D)(2\alpha_E+1)\alpha_D\right\}\left(\frac{V_3}{V_{1p}}\right)-$$

$$\left\{(2\alpha_E-1)+\mu^2\alpha_E(\alpha_E-2)-\left[\lambda_E+f(L/D)\right]+\mu^2 f(L/D)\right\}=0 \qquad (57)$$

Also, the nondimensionalized secondary velocity ratio V_{1s}/V_{1p} is given by

$$\left(\frac{V_{1s}}{V_{1p}}\right) = \frac{(\alpha_E+1)\alpha_D\left(\frac{V_3}{V_{1p}}\right)-1}{\alpha_E} \tag{58}$$

The thrust augmentation ratio ϕ for the ejector with forward speed V_α is given by

$$\phi = \frac{(\alpha_E+1)\alpha_D V_3 (V_3-V_\alpha)+V_{1p}V_\alpha}{V_{0p}^2} \tag{59}$$

Equation (59) can be expressed in the following form:

$$\phi = \frac{1}{\alpha_E^2-(1+\lambda_E)\left[(\alpha_E+1)\alpha_D\left(\frac{V_3}{V_{1p}}\right)-1\right]^2}\left\{\alpha_E^2(\alpha_E+1)(1-\mu^2)\alpha_D\left(\frac{V_3}{V_{1p}}\right)- \right.$$

$$\left. \mu\,\alpha_E\left[(\alpha_E+1)\alpha_D\left(\frac{V_3}{V_{1p}}\right)-1\right]\sqrt{\left\{\alpha_E^2-(1+\lambda_E)\left[(\alpha_E+1)\alpha_D\left(\frac{V_3}{V_{1p}}\right)-1\right]^2\right\}(1-\mu^2)}\,\right\}$$

$$\ldots(60)$$

where

$$\mu = \frac{V_\alpha}{V_{0p}} \tag{61}$$

The mass entrainment ratio w is

$$W = \alpha_E\left(\frac{V_{1s}}{V_{1p}}\right) \tag{62}$$

The above analysis is utilized to determine the effects of various flow losses, diffuser area ratios, and forward speed.

29

2. Effect of Flow Compressibility

As discussed previously, the effect of flow compressibility
is treated assuming no losses, no diffuser, and no forward
speed. This analysis utilizes the flow equations (1)
through (10), with the following conditions:

$$\left.\begin{array}{c} V_\alpha = f(L/D) = \lambda_E = \lambda_D = 0 \\[2mm] a_D = \eta_E = \eta_D = 1.0 \\[2mm] P_2 = P_a \end{array}\right\} \tag{63}$$

Using the above stipulated conditions, the jet ejector flow
equations (1) through (10) can now be reduced to seven
equations with seven unknowns, which are $\rho_{1p}, \rho_{1s}, \rho_2, V_{1p},$
V_{1s}, V_2, and P_1. These equations in their non-
dimensionalized form are as follows:

Continuity in the Mixing Chamber

$$\left(\frac{\rho_{1p}}{\rho_{ap}}\right)\left(\frac{V_{1p}}{V_{ap}}\right) + a_E\left(\frac{\rho_{1s}}{\rho_{ap}}\right)\left(\frac{V_{1s}}{V_{ap}}\right) = (a_E+1)\left(\frac{\rho_2}{\rho_{ap}}\right)\left(\frac{V_2}{V_{ap}}\right) \tag{64}$$

Momentum Across the Mixing Chamber

$$\frac{(a_E+1)(P_a-P_1)}{\rho_{ap}V_{ap}{}^2} = \frac{1}{g}\left(\frac{\rho_{1p}}{\rho_{ap}}\right)\left(\frac{V_{1p}}{V_{ap}}\right)^2 + \frac{a_E}{g}\left(\frac{\rho_{1s}}{\rho_{ap}}\right)\left(\frac{V_{1s}}{V_{ap}}\right)^2 - \frac{(a_E+1)}{g}\left(\frac{\rho_2}{\rho_{ap}}\right)\left(\frac{V_2}{V_{ap}}\right)^2$$

$$\dots (65)$$

Conservation of Energy in the Mixing Chamber

$$\left(\frac{\rho_{1p}}{\rho_{ap}}\right)\left(\frac{V_{1p}}{V_{ap}}\right) + a_E\left(\frac{\rho_{1s}}{\rho_{ap}}\right)\left(\frac{V_{1s}}{V_{ap}}\right)\left(\frac{T_a}{T_{op}}\right) = \frac{(a_E+1)}{c_p T_{op} J}\left(\frac{\rho_2}{\rho_{ap}}\right)\left(\frac{V_2}{V_{ap}}\right)\left(\frac{\gamma}{\gamma-1}\cdot\frac{P_2}{\rho_2}+\frac{V_2^2}{2g}\right)$$

$$\dots (66)$$

30

Conservation of Energy for the Primary Flow up to the Nozzle Exit

$$\frac{2 g c_p T_{0_p} J}{V_{a_p}{}^2} = \frac{2 g c_p T_{1_p} J}{V_{a_p}{}^2} + \left(\frac{V_{1_p}}{V_{a_p}}\right)^2 \tag{67}$$

Conservation of Energy for the Secondary Flow up to the Entrance to the Mixing Chamber

$$\frac{2 g c_p T_a J}{V_{a_p}{}^2} = \frac{2 g c_p T_{1_s} J}{V_{a_p}{}^2} + \left(\frac{V_{1_s}}{V_{a_p}}\right)^2 \tag{68}$$

Isentropic Process of the Primary Flows

$$\frac{P_1}{P_{0_p}} = \left[\frac{\gamma}{\gamma-1} \cdot \frac{P_1}{\rho_{1_p} c_p T_{0_p} J}\right]^{\frac{\gamma}{\gamma-1}} \tag{69}$$

Isentropic Process of the Secondary Flow

$$\frac{P_1}{P_a} = \left[\frac{\gamma}{\gamma-1} \cdot \frac{P_1}{\rho_{1_s} c_p T_a J}\right]^{\frac{\gamma}{\gamma-1}} \tag{70}$$

In these equations, ρ_{a_p} and V_{a_p} refer to the density and velocity, respectively, for the primary jet exhausted directly to the ambient and are given by

$$\rho_{a_p} = \frac{\gamma}{\gamma-1} \cdot \frac{P_a}{c_p T_{0_p} J} \left(\frac{P_{0_p}}{P_a}\right)^{\frac{\gamma-1}{\gamma}} \tag{71}$$

$$V_{a_p} = \sqrt{2 g c_p T_{0_p} J \left[1 - \left(\frac{P_a}{P_{0_p}}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{72}$$

31

The solution of the system of equations (64) through (70) is performed as follows:

From equations (69) and (70),

$$\left(\frac{\rho_{ls}}{\rho_{a_p}}\right) = \frac{\left(\dfrac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}}{\left(\dfrac{T_a}{T_{o_p}}\right)} \tag{73}$$

Substituting equation (72) into equation (67), there follows

$$\left(\frac{V_{lp}}{V_{a_p}}\right)^2 = \frac{1-\left(\dfrac{T_{lp}}{T_{o_p}}\right)}{1-\left(\dfrac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}} \tag{74}$$

Since

$$\left(\frac{T_{lp}}{T_{o_p}}\right) = \left(\frac{T_{lp}}{T_{a_p}}\right)\left(\frac{T_{a_p}}{T_{o_p}}\right)$$

and

$$\left(\frac{T_{a_p}}{T_{o_p}}\right) = \left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \left(\frac{T_{lp}}{T_{o_p}}\right) = \left(\frac{T_{lp}}{T_{a_p}}\right)\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}} \tag{75}$$

32

Substituting equation (75) into equation (74) yields

$$\left(\frac{V_{1p}}{V_{ap}}\right)^2 = \frac{1-\left(\frac{T_{1p}}{T_{ap}}\right)\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}}{1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}} \qquad (76)$$

Similarly, substituting equation (72) into equation (68),
there follows

$$\left(\frac{V_{1s}}{V_{ap}}\right)^2 = \frac{\left(\frac{T_a}{T_{op}}\right)\left[1-\left(\frac{T_{1s}}{T_a}\right)\right]}{1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}} \qquad (77)$$

Since

$$\left(\frac{T_{1s}}{T_a}\right) = \left(\frac{P_{1s}}{P_a}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\left(\frac{T_{1p}}{T_a}\right) = \left(\frac{P_{1p}}{T_{ap}}\right)^{\frac{\gamma-1}{\gamma}}$$

and

$$P_{1p} = P_{1s} = P_1$$

$$\therefore \quad \left(\frac{T_{1s}}{T_a}\right) = \left(\frac{T_{1p}}{T_{ap}}\right) \qquad (78)$$

33

Substituting equation (78) into equation (77) yeilds

$$\left(\frac{V_{1_S}}{V_{a_p}}\right)^2 = \frac{\left(\frac{T_a}{T_{o_p}}\right)\left[1 - \left(\frac{T_{1_p}}{T_{a_p}}\right)\right]}{1 - \left(\frac{P_a}{P_{o_p}}\right)^{\frac{1}{\gamma - 1}}} \tag{79}$$

Using the basic isentropic relationship,

$$\left(\frac{\rho_{1_p}}{\rho_{a_p}}\right) = \left(\frac{T_{1_p}}{T_{a_p}}\right)^{\frac{1}{\gamma - 1}} \tag{80}$$

Substituting equation (80) into (73) yields

$$\left(\frac{\rho_{1_S}}{\rho_{a_p}}\right) = \frac{\left(\frac{T_{1_p}}{T_{a_p}}\right)^{\frac{1}{\gamma - 1}}\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma - 1}{\gamma}}}{\left(\frac{T_a}{T_{o_p}}\right)} \tag{81}$$

From the equation of state,

$$P_a = \frac{\gamma - 1}{\gamma} c_p \rho_{a_p} T_{a_p} J$$

$$= \frac{\gamma - 1}{\gamma} c_p \rho_{a_p} T_{o_p} \left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma - 1}{\gamma}} J \tag{82}$$

34

Also, from the isentropic relationship,

$$\frac{P_1}{P_a} = \left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{\gamma}{\gamma-1}}$$

(83)

Substituting equation (82) into equation (83), there follows

$$P_1 = \frac{\gamma-1}{\gamma} c_p \rho_{ap} T_{op} \left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}} \left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{\gamma}{\gamma-1}} J$$

(84)

Making use of equation (64) and substituting equations (76), (77), (80), (81), (82), and (84) into equation (65), there results

$$\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}} \left\{ \sqrt{\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)\right]} + \right.$$

$$\left. \alpha_E \left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}} \sqrt{\frac{\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right]\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]}{\left(\frac{T_a}{T_{op}}\right)}} \right\} \left(\frac{V_2}{V_{ap}}\right) -$$

$$\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}} \left\{ 1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right) + \alpha_E \left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right] \right\} +$$

$$\left(\frac{\alpha_E+1}{2}\right)\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{\gamma}{\gamma-1}}\right] = 0$$

(85)

35

Similarly, equation (66) can be transformed as follows:

$$\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}}\left\{\sqrt{\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)\right]}\ +\right.$$

$$\left.\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\sqrt{\frac{\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right]}{\left(\frac{T_a}{T_{op}}\right)}}\right\}\left(\frac{V_2}{V_{ap}}\right)^2\ +$$

$$(\alpha_E+1)\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{V_2}{V_{ap}}\right)\ -$$

$$\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}}\left\{\sqrt{\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)\right]}\ +\right.$$

$$\left.\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\sqrt{\left(\frac{T_a}{T_{op}}\right)\left[1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right]}\right\}=0 \qquad (86)$$

Equations (85) and (86) are the two final equations which contain the unknowns T_{1p}/V_{ap} and V_2/V_{ap} and can be solved by an iteration method. It is seen that c_p, the specific heat at constant pressure, no longer appears in the equations.

The thermodynamic properties of the flows at different stations along the ejector can be expressed in terms of T_{1p}/T_{ap} and V_2/V_{ap} as follows:

36

$$\left(\frac{V_{1p}}{V_{ap}}\right) = \sqrt{\frac{1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)}{1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}}} \tag{87}$$

$$\left(\frac{V_{1s}}{V_{ap}}\right) = \sqrt{\frac{\left(\frac{T_a}{T_{op}}\right)\left[1-\left(\frac{T_{1p}}{T_{ap}}\right)\right]}{1-\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}}} \tag{88}$$

$$\left(\frac{\rho_{1p}}{\rho_{ap}}\right) = \left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}} \tag{89}$$

$$\left(\frac{\rho_{1s}}{\rho_{ap}}\right) = \frac{\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{1}{\gamma-1}}}{\left(\frac{T_a}{T_{op}}\right)} \tag{90}$$

$$\left(\frac{\rho_2}{\rho_{ap}}\right) = \frac{\left(\frac{\rho_{1p}}{\rho_{ap}}\right)\left(\frac{V_{1p}}{V_{ap}}\right) + \alpha_E\left(\frac{\rho_{1s}}{\rho_{ap}}\right)\left(\frac{V_{1s}}{V_{ap}}\right)}{(\alpha_E+1)\left(\frac{V_2}{V_{ap}}\right)} \tag{91}$$

$$\left(\frac{T_{1s}}{T_{ap}}\right) = \frac{\left(\frac{T_{1p}}{T_{ap}}\right)\left(\frac{T_a}{T_{op}}\right)}{\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}} \tag{92}$$

$$\left(\frac{T_2}{T_{ap}}\right) = \frac{1}{\left(\frac{\rho_2}{\rho_{ap}}\right)} \tag{93}$$

$$\left(\frac{P_1}{P_a}\right) = \left(\frac{T_{1p}}{T_{ap}}\right)^{\frac{\gamma}{\gamma-1}} \tag{94}$$

37

$$M_{1p} = \sqrt{\frac{2}{\gamma-1}\left[\frac{1-\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{a_p}}\right)}{\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{1p}}{T_{a_p}}\right)}\right]} \tag{95}$$

$$M_{1s} = \sqrt{\frac{2}{\gamma-1}\left[\frac{1}{\left(\frac{T_{1p}}{T_{a_p}}-1\right)}\right]} \tag{96}$$

$$M_2 = \sqrt{\frac{2}{\gamma-1}\left(\frac{\rho_2}{\rho_{a_p}}\right)\left[\frac{1-\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}}{\left(\frac{P_a}{P_{o_p}}\right)^{\frac{\gamma-1}{\gamma}}}\right]} \tag{97}$$

Finally, the thrust augmentation ratio ϕ and the mass entrainment ratio w can be determined as follows:

$$\dot{\phi} = (\alpha_E+1)\left(\frac{\rho_2}{\rho_{a_p}}\right)\left(\frac{V_2}{V_{a_p}}\right)^2 \tag{98}$$

$$W = \alpha_E\frac{\left(\frac{\rho_{1s}}{\rho_{a_p}}\right)\left(\frac{V_{1s}}{V_{a_p}}\right)}{\left(\frac{\rho_{1p}}{\rho_{a_p}}\right)\left(\frac{V_{1p}}{V_{a_p}}\right)} \tag{99}$$

3. Nonuniform Velocity Profile at the Secondary Entrance

In both the idealized and practical analyses, a one-dimensional approach is used which assumes the secondary flow

velocity at the entrance plane as uniform, irrespective of the secondary-to-primary area ratio. For the case of no diffuser, the idealized analysis yields a maximum thrust augmentation ratio of 2.0 at an infinite area ratio. This is obviously not correct, because when the area ratio tends to infinity, the ejector configuration reduces to a free jet, in which case the augmentation ratio must be unity. It is believed that this discrepancy is caused by the assumption of the uniform flow velocity at the secondary entrance. In other words, the applicability of the one-dimensional approach is limited to not too large secondary-to-primary area ratios, and a three-dimensional analysis is required for relatively large area ratios. However, such a task has never been undertaken by any of the investigators, and it is beyond the scope of this program to formulate a solution to this complex problem.

Instead, an empirical correction factor is herein developed to account for the effect of the nonuniform secondary flow velocity profile. The derivation of this factor is as follows:

Under the assumption of uniform secondary flow velocity, the momentum equation for the control volume inside the mixing chamber with no diffuser and no losses becomes:

$$(\alpha_E + 1)(P_0 - \overline{P}_1) = \frac{\rho}{g}\left[\overline{V}_{1_p}^{\,2} + \alpha_E \overline{V}_{1_s}^{\,2} - (\alpha_E + 1)\overline{V}_2^{\,2}\right] \tag{100}$$

By using Bernoulli's equation for the secondary flow and the ambient conditions in front of the ejector, equation (100) is reduced to

$$\left(\frac{\overline{V}_2}{\overline{V}_{1_p}}\right)^2 = \frac{1 + \left(\frac{\alpha_E - 1}{2}\right)\left(\frac{\overline{V}_{1_s}}{\overline{V}_{1_p}}\right)^2}{\alpha_E + 1} \tag{101}$$

In these equations, the "bar" denotes uniform values.

39

If the secondary velocity is not uniform, the momentum equation becomes

$$(\alpha_E + 1) P_O - \overline{P}_1 - \frac{\alpha_E \int P_{1s} dA_{1s}}{A_{1s}}$$

$$= \frac{\rho}{g}\left[\overline{V}_{1p}^{2} + \frac{\alpha_E \int V_{1s}^{2} dA_{1s}}{A_{1s}} - (\alpha_E + 1) V_2^{2}\right] \qquad (10\ )$$

The solution of equation (102) for $(V_2/\overline{V}_{1p})$ is based on the following assumptions:

(a) The primary velocity at the entrance plane is still the same as in the case of uniform secondary velocity.

(b) The primary pressure at the entrance plane is the same as in the case of uniform secondary velocity. Hence, $\overline{P}_{1p} = \overline{P}_1$

(c) The exit velocity of the mixed flow V_2, though different from that in the case of uniform secondary velocity, is uniform at the mixing chamber exit.

Since the secondary flow has a uniform stagnation pressure P_O far upstream, by assuming parallel streamlines at the entrance plane it is possible to evaluate the static pressure distribution P_{1s} by making use of Bernoulli's equation. Thus, equation (102) is finally reduced to

$$\left(\frac{V_2}{\overline{V}_{1p}}\right)^2 = \frac{1 + \dfrac{\alpha_E \int \left(\dfrac{V_{1s}}{\overline{V}_{1p}}\right)^2 dA_{1s}}{2A_{1s}} - \dfrac{1}{2}\left(\dfrac{\overline{V}_{1s}}{\overline{V}_{1p}}\right)^2}{\alpha_E + 1} \qquad (103)$$

40

Equations (101) and (103) yield the exit-to-primary velocity ratios based on uniform and nonuniform secondary entrance velocity profiles, respectively. The corresponding thrust augmentation ratios for the two cases are given below.

The thrust augmentation ratio for the case of uniform secondary velocity is

$$\bar{\phi} = \frac{(\alpha_E + 1)\left(\dfrac{\bar{V}_2}{\bar{V}_{1p}}\right)^2}{\left(\dfrac{\bar{V}_{ap}}{\bar{V}_{1p}}\right)^2} \tag{104}$$

where $\bar{V}_{ap}/\bar{V}_{1p}$ and $\bar{V}_2/\bar{V}_{1p}$ can be obtained from the idealized theoretical analysis as follows:

$$\left(\frac{\bar{V}_{ap}}{\bar{V}_{1p}}\right)^2 = 1 - \frac{2\left[(\alpha_E + 1)\left(\dfrac{\bar{V}_2}{\bar{V}_{1p}}\right)^2 - 1\right]}{\alpha_E - 1} \tag{105}$$

and

$$\left(\frac{\bar{V}_2}{\bar{V}_{1p}}\right)^2 = \left[\frac{-(\alpha_E - 1) + \alpha_E\sqrt{2\alpha_E}}{\alpha_E^2 + 1}\right]^2 \tag{106}$$

41

For the nonuniform case, the thrust augmentation ratio is

$$\phi = \frac{(\alpha_E + 1)\left(\dfrac{V_2}{\overline{V}_{1p}}\right)^2}{\left(\dfrac{\overline{V}_{ap}}{\overline{V}_{1p}}\right)^2} \qquad (107)$$

where $\left(V_2/\overline{V}_{1p}\right)^2$ as given by equation (103) will be determined below.

The correction factor for thrust augmentation ratio due to nonuniform velocity profile at the secondary entrance is herein defined as

$$\chi = \frac{\phi}{\overline{\phi}} = \frac{\left(\dfrac{V_2}{\overline{V}_{1p}}\right)^2}{\left(\dfrac{\overline{V}_2}{\overline{V}_{1p}}\right)^2} \qquad (108)$$

It is now necessary to establish relationships for $V_{1s}/\overline{V}_{1p}$ and $\overline{V}_{1s}/\overline{V}_{1p}$ to determine $V_2/\overline{V}_{1p}$ given by equation (103). According to Reference 26, the velocity profile of a flow entrained by a free jet can be well approximated by a cosine curve. Therefore, it is reasonable to assume that a cosine curve distribution, as shown in Figure 2, will adequately represent the velocity profile at the secondary entrance of a jet ejector system.

It is further assumed that the local secondary velocity at the jet periphery ⓐ is the same as the uniform velocity $\overline{V}_{1s}$. Thus, the secondary entrance velocity profile at any radial station can be expressed as follows:

$$V_{1s} = \frac{1 + \cos\dfrac{(r'-1)\,\pi}{\kappa}}{2}\,\overline{V}_{1s} \qquad (109)$$

42
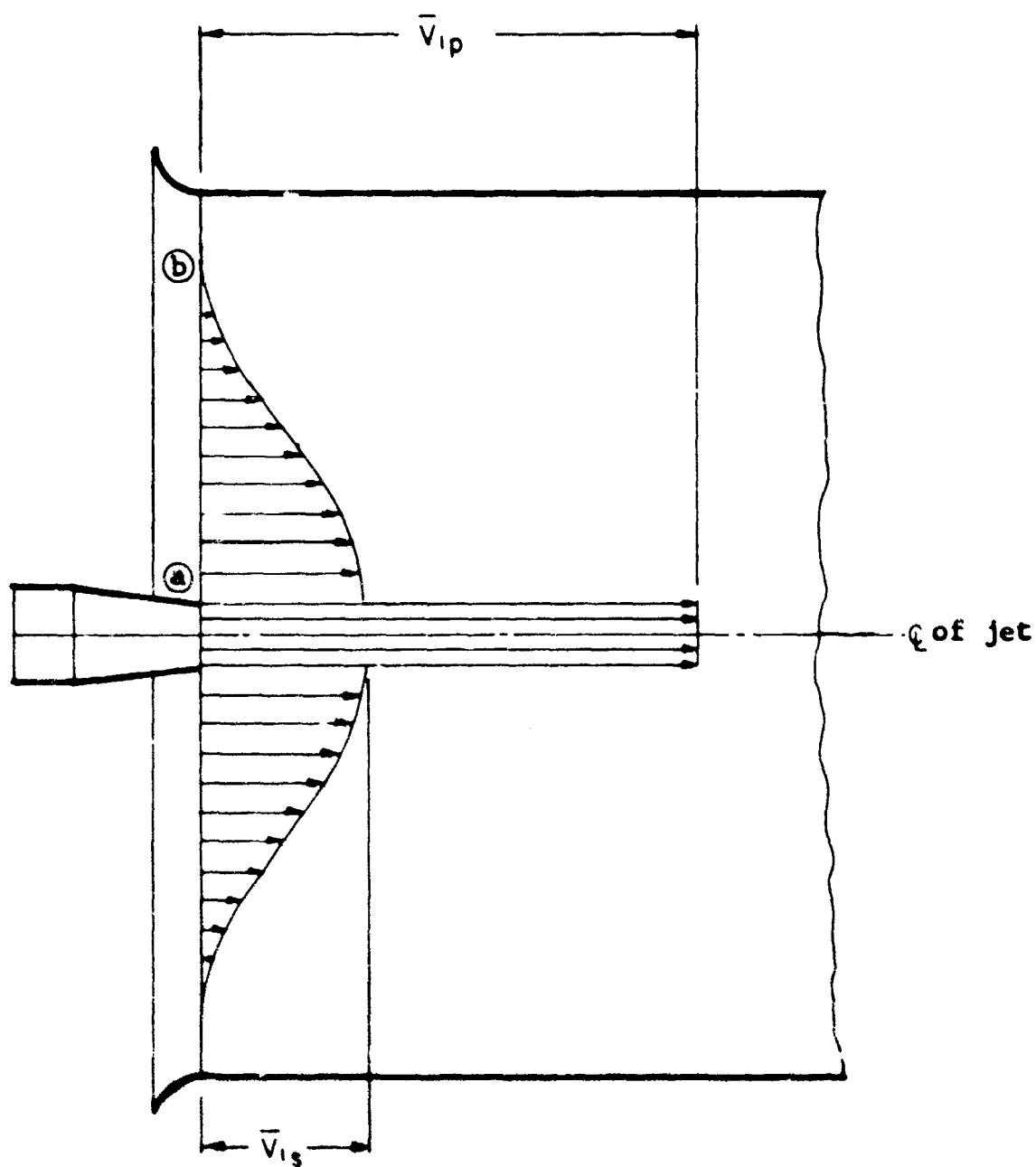
Figure 2. Nonuniform Velocity Profile at Secondary Entrance.

43

In equation (109), r' is the radial distance from the ejector center line, nondimensionalized by the jet radius, and κ, is a constant defining flow nonuniformity at the secondary entrance. This equation applies only for the range $0 \leq (r'-1)/\kappa \leq 1$. In other words, as shown in **Figure 2**, the local velocity V_{ls} gradually decreases to zero at point ⓑ and maintains zero at any larger radial distance from the ejector center line. The location of point ⓑ depends on the constant κ.

By assigning a suitable value of κ, the integral $\int (V_{ls}/\overline{V}_{lp})^2 \, dA_{ls}/A_{ls}$ in equation (103) can be evaluated for all values of α_E in terms of $\overline{V}_{ls}$. Let

$$\xi = \frac{\int V_{ls}^2 \, dA_{ls}}{\overline{V}_{ls}^2 A_{ls}} \tag{110}$$

Substituting equation (109) into equation (110), there results

$$\xi = \frac{\alpha_E + 1}{2} \int_0^1 \left[1 + \cos \frac{(r'-1)\pi}{\kappa} \right] r' \, dr' \tag{111}$$

Integrating equation (111) with respect to r' yields

$$\xi = \frac{3}{8} + \frac{\kappa \sqrt{\alpha_E + 1}}{4 \alpha_E \pi} \sin \frac{(\sqrt{\alpha_E + 1} - 1)\pi}{\kappa} \left[4 + \cos \frac{(\sqrt{\alpha_E + 1} - 1)\pi}{\kappa} \right] -$$

$$\frac{\kappa^2}{8 \alpha_E \pi^2} \left[1 - \cos \frac{(\sqrt{\alpha_E + 1} - 1)\pi}{\kappa} \right] \left[9 + \cos \frac{(\sqrt{\alpha_E + 1} - 1)\pi}{\kappa} \right] \tag{112}$$

for $\alpha_E \leq \kappa(\kappa + 2)$ and

$$\xi = \frac{3\kappa(\kappa + 2)\pi^2 - 16\kappa^2}{8\alpha_E \pi^2} \tag{113}$$

for $\alpha_E \leq \kappa(\kappa + 2)$

44

The correction factor for the thrust augmentation ratio given by equation (108) thus becomes

$$\chi = \frac{1 + \dfrac{\xi}{2} \dfrac{\alpha_E - 1}{} \left(\dfrac{\overline{V}_{1s}}{\overline{V}_{1p}}\right)^2}{1 + \dfrac{\alpha_E - 1}{2} \left(\dfrac{\overline{V}_{1s}}{\overline{V}_{1p}}\right)} \tag{114}$$

where ξ is given by equation (112) or (113) and $\overline{V}_{1s}/\overline{V}_{1p}$ can be obtained from the idealized analysis equation (32) as follows:

$$\frac{\overline{V}_{1s}}{\overline{V}_{1p}} = \frac{(\alpha_E + 1)\left[-(\alpha_E - 1) + \alpha_E \sqrt{2\alpha_E}\right] - (\alpha_E^2 + 1)}{\alpha_E(\alpha_E^2 + 1)} \tag{115}$$

Equation (114) is utilized to compute the thrust augmentation ratio ϕ as affected by the nonuniform velocity distribution at the secondary entrance. The results are herein presented in Figure 3, which shows the variation of ϕ vs. α_E for constant values of the parameter κ. By examining this figure, it can be noted that as κ tends to infinity, the ϕ vs. α_E relationship reduces to that as obtained by the idealized analysis with uniform secondary velocity profile. Also, for any finite value of κ, ϕ reaches a maximum value (less than 2.0) at a finite α_E and then decreases to unity as α_E tends to infinity.

In order to determine the parameter κ, appropriate test data are required which could be used to determine the area ratio α_E at which the thrust augmentation ratio is maximum. However, most of the available test data (see Section VI) are obtained for ejectors having area ratios α_E of less than 100, at which values the thrust augmentation ratio ϕ does not reach a maximum value. For example, the correlation shown in Table II (Section VII) indicates that at an area ratio of $\alpha_E = 104$, the rate of increase of ϕ with α_E is quite small. It is reasonable to assume, therefore, that for α_E ranging

45

Figure 3. Effect of κ on Thrust Augmentation Ratio.

46
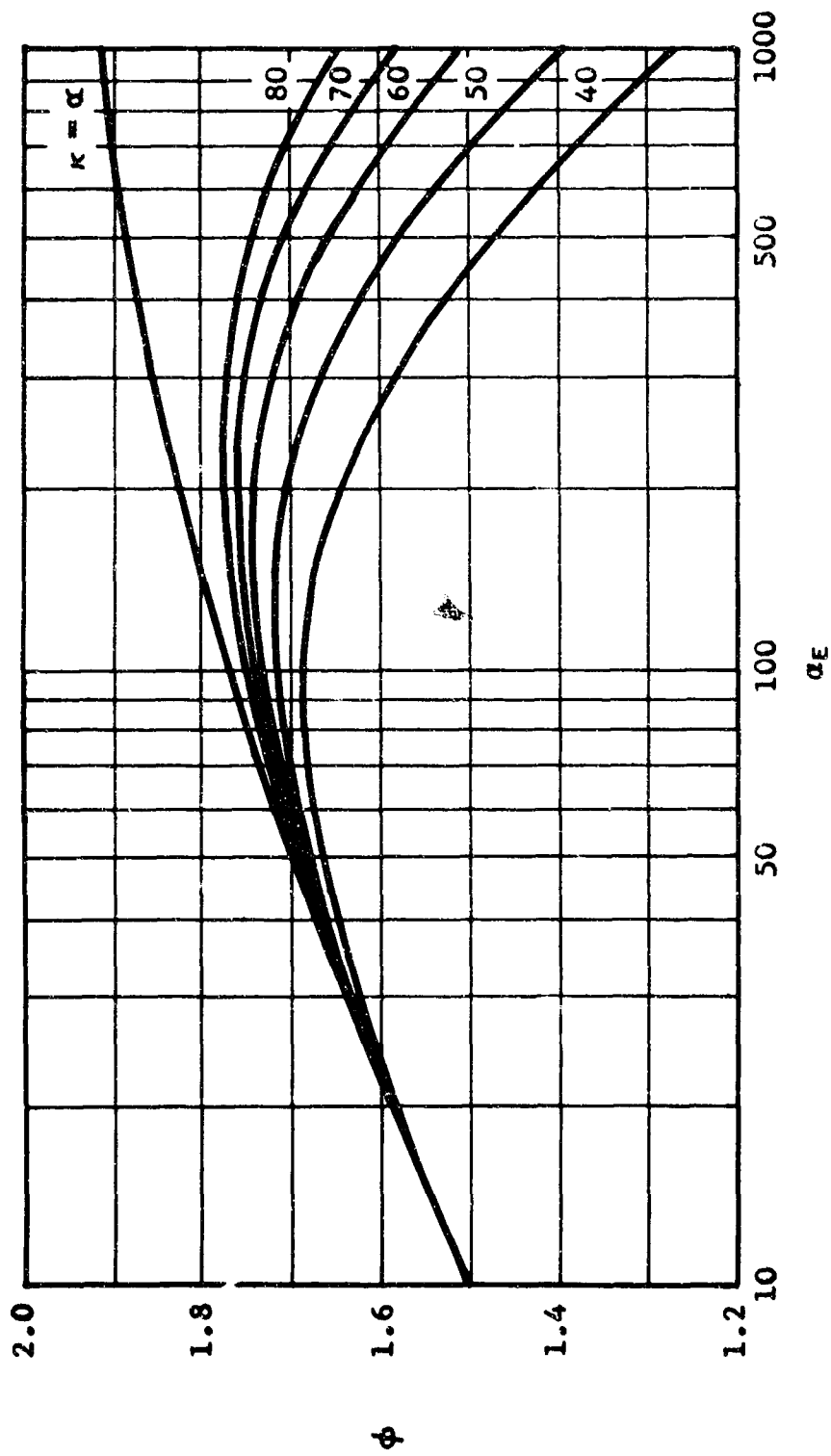
from 150 to 200, the thrust augmentation would have reached its peak value. Therefore, it follows from Figure 3 that a practical value of the parameter κ would be between $\kappa = 60$ and $\kappa = 70$. This, however, necessitates further experimental evidence.

4. Analysis of Various Ejector Types

The most common types of jet ejectors consist of either single nozzle, multiple nozzle, or annular nozzle configurations. These configurations differ from each other primarily in the efficiency at which the primary, low momentum flow is converted into a high momentum flow. The conversion takes place in the mixing chamber, which, in order to reduce wall friction losses, should be of minimum length. No precise method exists at present to determine the minimum mixing chamber length required to achieve complete mixing between the primary and secondary flows. The following analysis will provide, however, a first-order approximation of the relative effects of the different configurations on the mixing chamber length.

First, it is assumed that the mixing chamber consists of two parts as shown in Figure 4. The first part (L_1) , which allows for the primary jet expansion, starts at the jet exit and ends at a point where the jet boundary reaches the ejector walls. The second part (L_2) starts from thereon and extends to the exit of the mixing chamber, where the mixing process is assumed to be completed.

a. Single Nozzle Configuration

The work of Squire and Trouncer (Reference 19) is utilized to determine the length (L_1) for a single-nozzle primary flow configuration.

In this reference an analysis is performed for determining the expansion angle of a single, circular jet discharging into a free stream of uniform velocity. If it is assumed that this expansion angle is not affected by the presence of the mixing chamber walls, the primary jet boundaries can be plotted as a function of the secondary flow velocity as shown in Figure 5. In this figure the

47
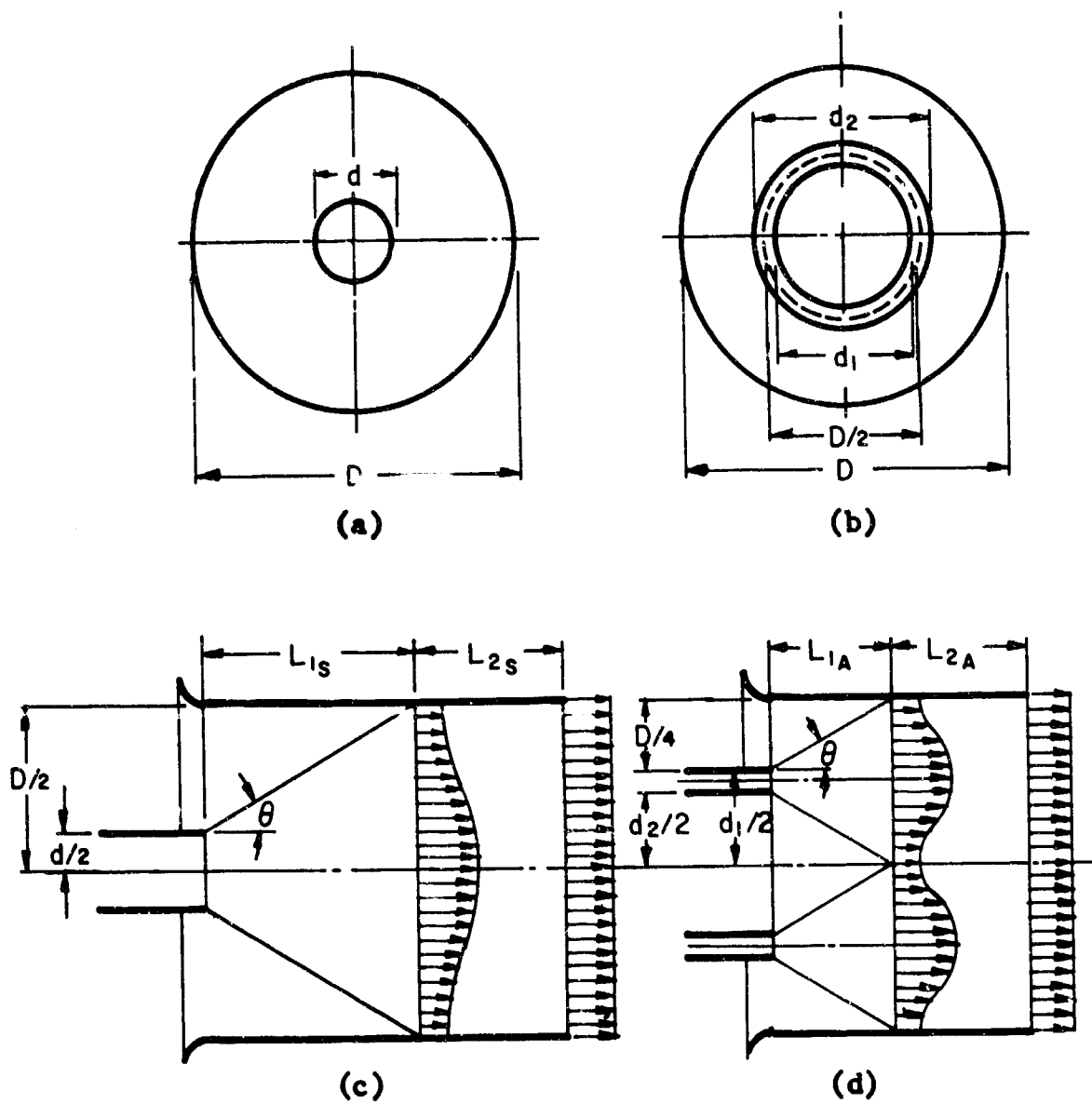
Figure 4. Definition of Parameters for
Single and Annular Nozzle Configurations.
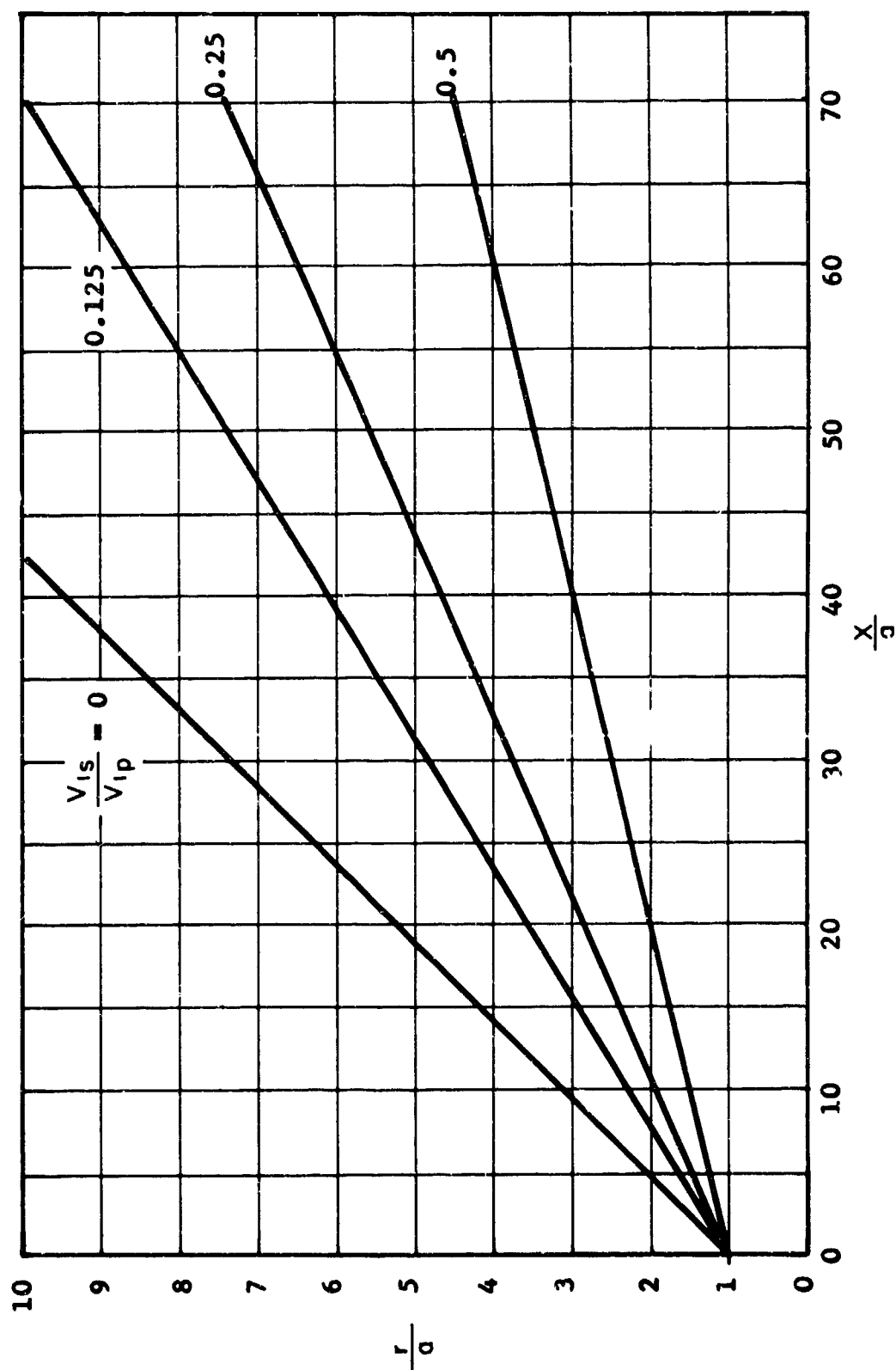
Figure 5. Jet Boundaries.

49

streamwise distance from the primary jet exit is
denoted by X, and the radial distance of the jet
boundary from the jet center line is denoted by r.
Typical variations of V_{IS}/V_{Ip} versus secondary-to-
primary area ratio α_E are shown in Figure 6.

Using Figures 5 and 6, the length L_I can now be
determined as follows:

(i) A value α_E is assumed, and from
Figure 6 the corresponding value of
V_{IS}/V_{Ip} is obtained.

(ii) The value of r/a is obtained from the
following relationship:

$$r/a = \sqrt{\alpha_E + 1} \qquad (116)$$

(iii) With the above values of V_{IS}/V_{in} and r/a,
the corresponding value of X/a is
obtained from Figure 5.

(iv) Finally,

$$\frac{L_I}{D} = \frac{1}{2}\left(\frac{X/a}{r/a}\right) \qquad (117)$$

The above calculations were repeated for several
values of α_E, and the results are plotted in
Figure 7 for the incompressible and the compressible
analyses. Similar curves can also be obtained
including various flow losses. Figure 7 indicates
that, for practical values of α_E, the ratio (L_I/D)
is of the order of 3 to 4.

Insufficient data exist to determine the length of
the second part of the mixing chamber, L_2.
However, it will be assumed that this length is
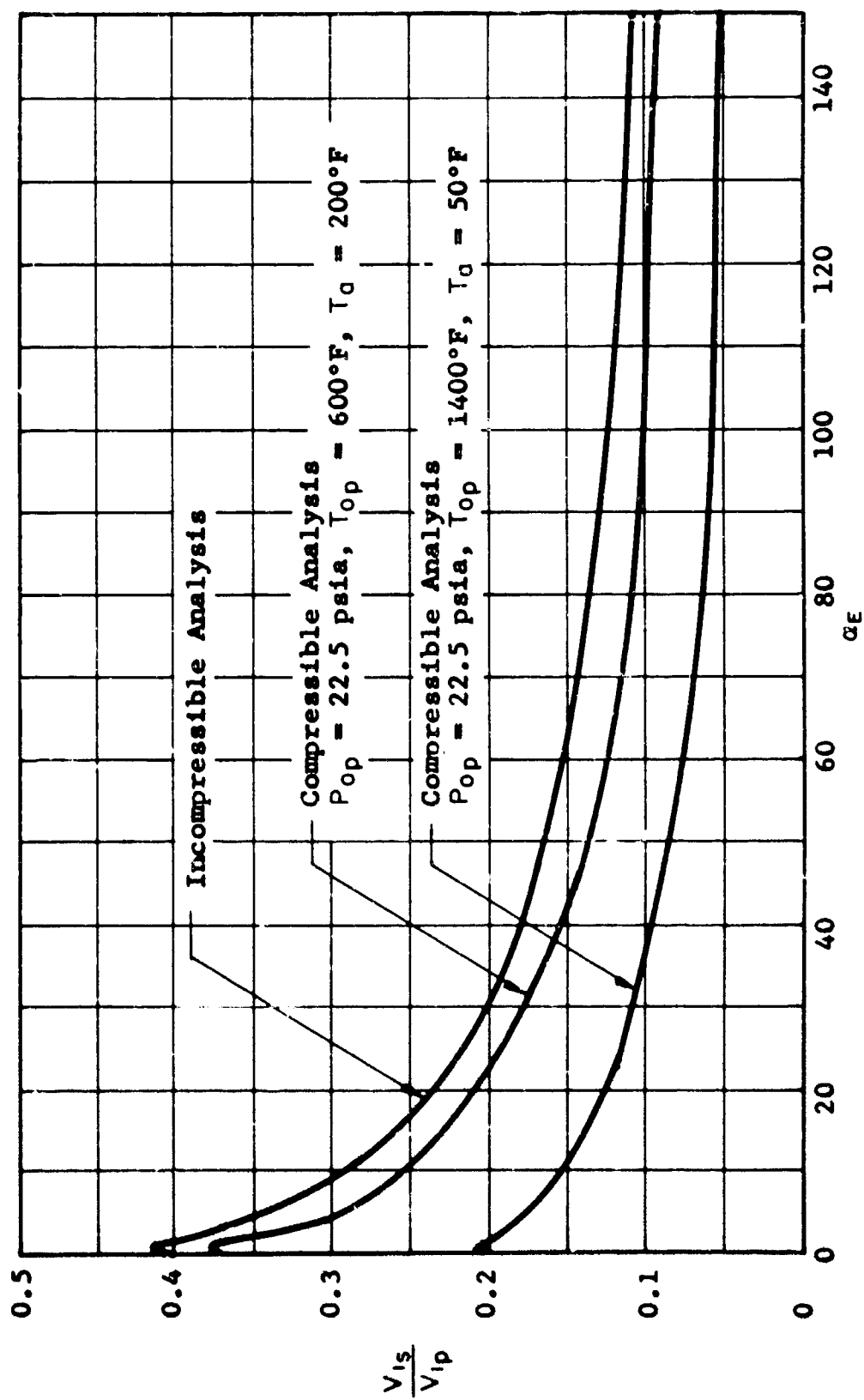
Figure 6. Variation of Secondary-to-Primary Velocity Ratio with Secondary-to-Primary Area Ratio (No Diffuser; No Forward Speed; No Losses).
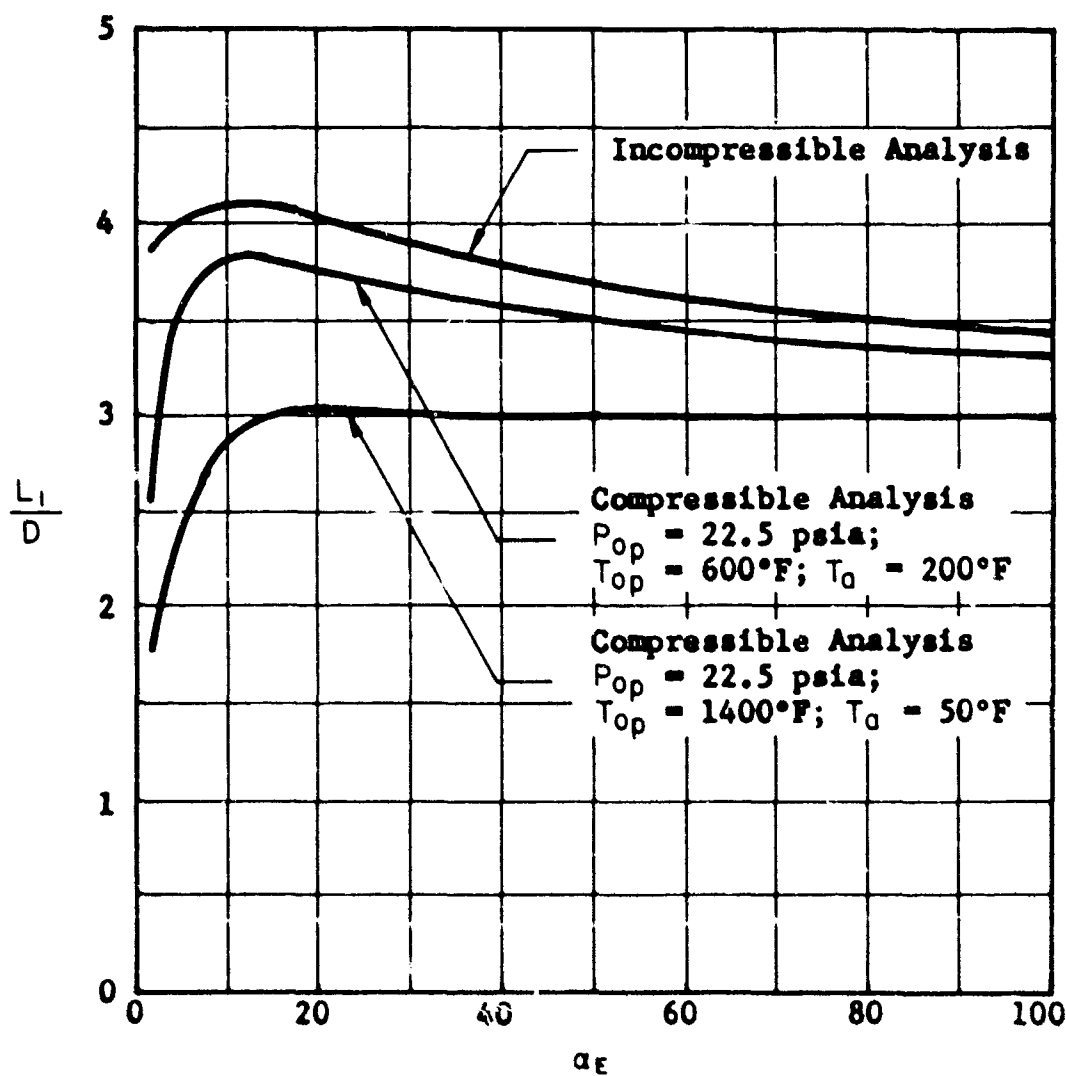
Figure 7. Variation of Length of the First Part of Mixing Chamber with Secondary-to-Primary Area Ratio (No Diffuser; No Forward Speed; No Losses).

proportional to the contact surface area between the primary and the surrounding flows.

b. Multiple Nozzle Configuration

The first portion of the mixing chamber length, L_1, for a multiple nozzle configuration can easily be determined for the two-dimensional ejector by assuming that these nozzles are evenly spaced with respect to the mixing chamber and with respect to each other.

For a multiple nozzle configuration having N number of nozzles of the same total area as the single central nozzle, $(A_{1p})_s$, the primary area of each nozzle is

$$(A_{1p})_M = \frac{1}{N} (A_{1p})_s \tag{118}$$

Also, if the total secondary area of the multiple and single nozzle configurations is the same, it follows that

$$(A_{1s})_M = \frac{1}{N} (A_{1s})_s \tag{119}$$

Therefore, from equations (118) and (119) it follows that the secondary-to-primary area ratio for each nozzle of multiple nozzle configuration is the same as that for the corresponding single central nozzle type, i.e.,

$$(\alpha_E)_M = \frac{(A_{1s})_M}{(A_{1p})_M} = \frac{(A_{1s})_s}{(A_{1p})_s} = (\alpha_E)_s \tag{120}$$

53

Since the area ratios are the same (equation 120),
using Figure 7, the effective (L_1/D) for each
nozzle of the multiple nozzle configuration is the
same as that for the single nozzle design, i.e.,

$$\left(\frac{L_1}{D}\right)_M = \left(\frac{L_1}{D}\right)_S \tag{121}$$

From equation (119), the diameter of the effective
mixing chamber for each nozzle of the multiple
nozzle configuration can be determined as follows:

$$\left(\frac{\pi D}{4}\right)^2_M = \frac{1}{N}\left(\frac{\pi D}{4}\right)^2_S \tag{122}$$

or

$$(D)_M = \frac{1}{\sqrt{N}}(D)_S \tag{123}$$

From equations (121) and (123), it follows that the
mixing chamber length (L_1) required for the jet
boundary to reach the ejector walls for the multiple
nozzle configuration is reduced by a factor of
$1/\sqrt{N}$ of the corresponding single nozzle length.
Thus,

$$(L_1)_M = \frac{1}{\sqrt{N}}(L_1)_S \tag{124}$$

Assuming that the second part of the mixing chamber
length L_2 is a function of the total contact area
of the primary flow with the surrounding air, the
relationship for the mixing chamber lengths $(L_2)_M$
and $(L_2)_S$ of multiple and single nozzle configura-
tions can be obtained as follows:

54

The contact area of the primary jet with the surrounding flow for a single central nozzle type is given by

$$(S)_S = \pi (D)_S (L_2)_S \tag{125}$$

Similarly, the total contact area of the primary jet for a multiple nozzle configuration of N nozzles is

$$(S)_M = N \pi (D)_M (L_2)_M \tag{126}$$

Substituting equation (123) into (126) yields

$$(S)_M = \sqrt{N} \, \pi (D)_S (L_2)_M \tag{127}$$

Assuming that in each case the contact areas are such as to produce complete mixing at the exit of the mixing chamber, equations (125) and (127) yield

$$(L_2)_M = \frac{1}{\sqrt{N}} (L_2)_S \tag{128}$$

Combining equations (124) and (128), there follows

$$(L)_M = \frac{1}{\sqrt{N}} (L)_S \tag{129}$$

55

Equations (124), (128), and (129) indicate that for
a multiple nozzle jet ejector configuration, each
part of the mixing chamber length as well as the
total length reduces by a factor of $1/\sqrt{N}$ as
compared with the single central nozzle configura-
tion. This reduction in the mixing chamber length
results in the reduction of head loss due to wall
friction. Therefore, the multiple nozzle configu-
ration would yield a superior performance as
compared to that of the equivalent single nozzle
ejector if the complete mixing conditions at the
exit of the mixing chamber are satisfied in each
case.

c. **Annular Nozzle Configuration**

For the case of an annular primary jet located
midway between the walls and the center of the
mixing chamber walls, both parts of the mixing
chamber lengths $(L_1)_A$ and $(L_2)_A$, as discussed above,
will also substantially reduce as compared to the
equivalent single nozzle configuration.

The analysis for determining the mixing chamber
lengths for the annular nozzle ejector can be
performed as follows:

Using Figure 4(a), the primary area of the single
nozzle configuration is given by

$$(A_{1p})_s = \frac{\pi}{4} d^2 \tag{130}$$

From Figure 4(b), the corresponding primary area
for the annular nozzle is

$$(A_{1p})_A = \frac{\pi}{4} (d_2^2 - d_1^2) \tag{131}$$

56

For the same primary jet areas, equations (130)
and (131) yield

$$d^2 = d_2^2 - d_1^2 = (d_2 + d_1)(d_2 - d_1) \qquad (132)$$

Since the annular jet is centrally located within
the mixing chamber having a fixed diameter D, it
follows that

$$\frac{d_2 + d_i}{2} = \frac{D}{2} \qquad (133)$$

Equations (132) and (133) yield

$$d_2 - d_1 = \frac{d^2}{D} \qquad (134)$$

Since the primary jet areas for the two configura-
tions are the same and since outside diameters D
of the mixing chambers are also the same, it
follows that

$$(A_{I_S})_S = (A_{I_S})_A = \frac{\pi}{4}(D^2 - d^2) \qquad (135)$$

From the above analysis it therefore follows, that
the secondary-to-primary area ratio of the annular
nozzle ejector is equal to that of the equivalent
single central nozzle configuration, i.e.,

$$(\alpha_E)_A = (\alpha_E)_S$$

57

Using equations (130) and (135), the corresponding secondary-to-primary area ratios are

$$\alpha_E = \frac{A_{Is}}{A_{Ip}} = \frac{D^2}{d^2} - 1 \qquad (136)$$

$$\therefore \quad \frac{D}{d} = \sqrt{\alpha_E + 1} \qquad (137)$$

Assuming identical primary jet stagnation conditions, the velocity ratios V_{is}/V_p will also be equal. Using Figure 5, it therefore follows that the primary jet expansion angle,

$$\theta = \tan^{-1}\left(\frac{r/a}{X/a}\right) \quad ,$$

for annular nozzle configuration and the corresponding single jet will be the same. Thus, using Figure 4(c), the first part of the mixing chamber length for a single nozzle configuration can be expressed as follows:

$$(L_1)_S = \frac{D-d}{2} \cdot \frac{1}{\tan\theta} \qquad (138)$$

Similarly, using Figure 4(d), the corresponding length for the annular nozzle ejector is

$$(L_1)_A = \frac{D-(d_2-d_1)}{4} \cdot \frac{1}{\tan\theta} \qquad (139)$$

58

Equations (138) and (139) yield

$$\frac{(L_1)_A}{(L_1)_S} = \frac{1}{2}\left[\frac{D-(d_2-d_1)}{D-d}\right] \tag{140}$$

Substituting equation (134) into equation (140), there follows

$$\frac{(L_1)_A}{(L_1)_S} = \frac{1}{2}\left(1+\frac{d}{D}\right) \tag{141}$$

Substituting equation (137) into (141) yields

$$\frac{(L_1)_A}{(L_1)_S} = \frac{1}{2}\left(1+\frac{1}{\sqrt{\alpha_E+1}}\right) \tag{142}$$

or

$$(L_1)_A = \frac{1}{2}\left(1+\frac{1}{\sqrt{\alpha_E+1}}\right)(L_1)_S \tag{143}$$

Equation (143) shows that the first part of the mixing length $(L_1)_A$ for the annular nozzle configuration is a function of the area ratio α_E and that for large values of α_E it is approximately equal to a half that of the corresponding single central nozzle ejector. For small values of the area ratios, this length approaches $(L_1)_S$.

The second part of the mixing chamber length for the annular nozzle ejector can be determined as follows:

59

The surface contact area of the primary jet with the surrounding flow for a single nozzle ejector is

$$(S)_S = \pi\, d\, (L_2)_S \qquad (144)$$

The corresponding contact area for the annular jet is given by

$$(S)_A = \pi\, (d_2 + d_1)(L_2)_A \qquad (145)$$

Assuming that in each case the same constant contact surface area is required to complete the mixing process at the exit of the mixing chamber, equations (144) and (145) yield

$$(L_2)_A = \frac{d}{d_2 + d_1}\,(L_2)_S \qquad (146)$$

Substituting equation (143) into (146) yields

$$(L_2)_A = \frac{d}{D}\,(L_2)_S \qquad (147)$$

From equations (142) and (147), there results

$$(L_2)_A = \frac{1}{\sqrt{\alpha_E + 1}}\,(L_2)_S \qquad (148)$$

Equation (148) shows that the second part of the mixing chamber length for the annular nozzle configuration reduces by a factor of $1/\sqrt{\alpha_E + 1}$ as compared to that of the equivalent single jet ejector.

60

Finally, using equations (143) and (148), the total mixing length for the annular jet ejector is given by

$$(L)_A = \frac{1}{2}\left(1 + \frac{1}{\sqrt{\alpha_E + 1}}\right)(L_1)_s + \frac{1}{\sqrt{\alpha_E + 1}}(L_2)_s \qquad (149)$$

V. EFFECT OF PARAMETERS ON JET EJECTOR PERFORMANCE

Presented in this section are the results of a study showing
the effects of various aerodynamic, thermodynamic, and
geometric flow parameters on ejector thrust augmentation
performance. The study includes the following parameters:

A. FLOW LOSSES

The effect of flow losses is to reduce ejector performance.
This effect can be clearly seen from the nomographs of
Section VII and requires no further explanation.

B. DIFFUSER

The results of the idealized analysis presented in Figures 8
and 9 show that under static conditions, at any secondary-to-
primary area ratio, an increase in diffuser area ratio yields
better thrust augmentation performance. However, as shown in
Figure 10, this is not true for a practical case when the
flow losses are included. Although the overall diffuser loss
factor λ_D varies with the area ratio α_D, for the purpose of
this duscussion all flow losses including the diffuser loss
factor λ_D are held constant (at typical values) for all
diffuser area ratios.

Examining Figure 10, it can be seen that for any pracitcal
value of secondary-to-primary area ratio α_E, the thrust
augmentation ratio ϕ reaches an optimum value with the
diffuser area ratio α_D ranging between 1.5 and 2.0. For the
diffuser area ratios larger than 2.0, the thrust augmentation
ratio would be actually lower than that indicated in
Figure 10 as a result of increase in the diffuser loss factor
λ_D with increase of α_D.

C. FORWARD SPEED

Figure 11 shows the effect of forward speed on thrust
augmentation ratio for an idealized condition with no flow
losses and no diffuser. It can be seen from this figure
that an increase in forward speed results in a substantial
reduction of thrust augmentation ratio for all secondary-to-
primary area ratios, α_E. Furthermore, for any specific
nonzero value of forward speed, the thrust augmentation
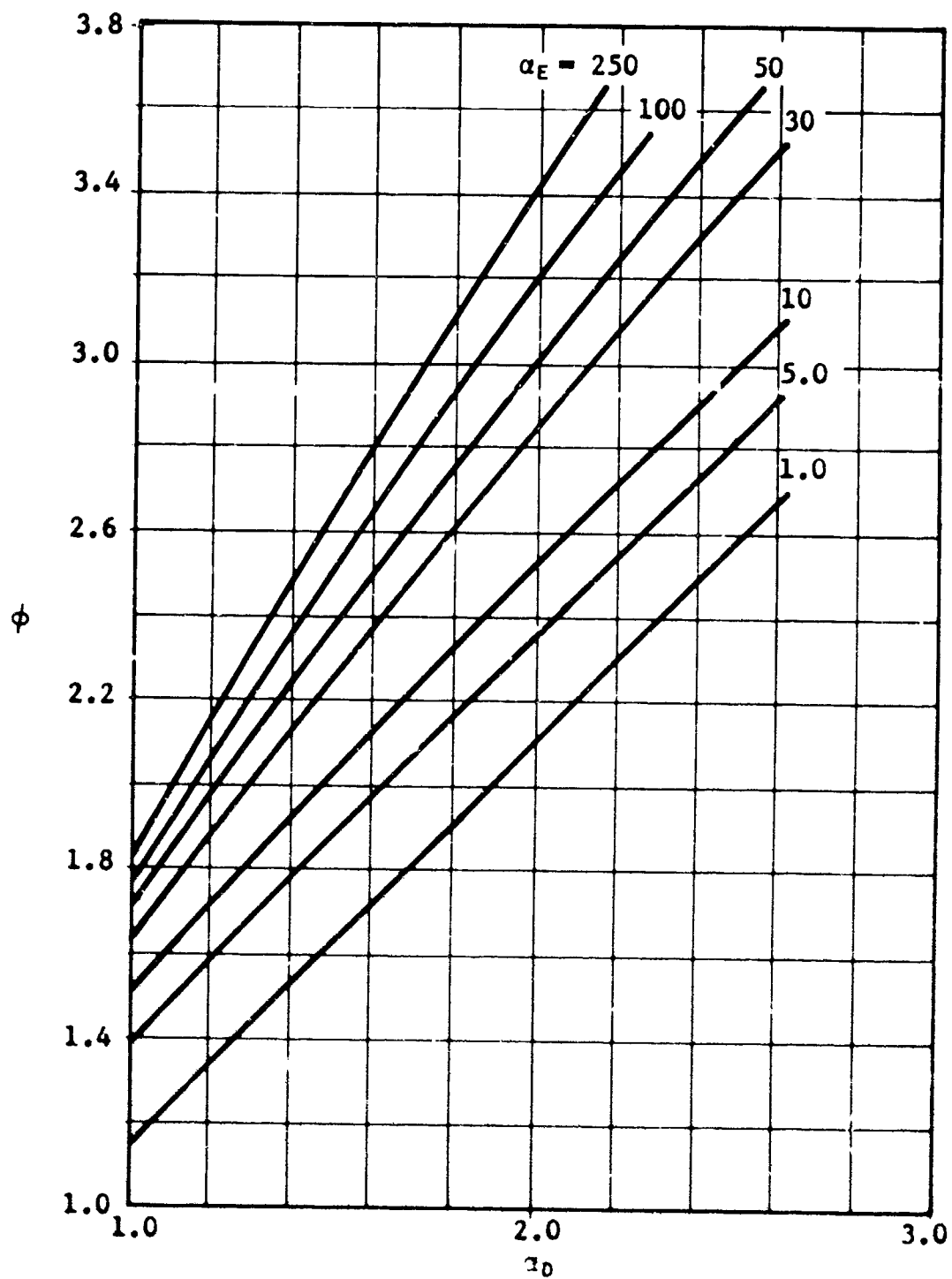
Figure 8.   Effect of Diffuser on Thrust Augmentation of a Jet Ejector with Constant Area Mixing Chamber (No Forward Speed, No Flow Losses).

63
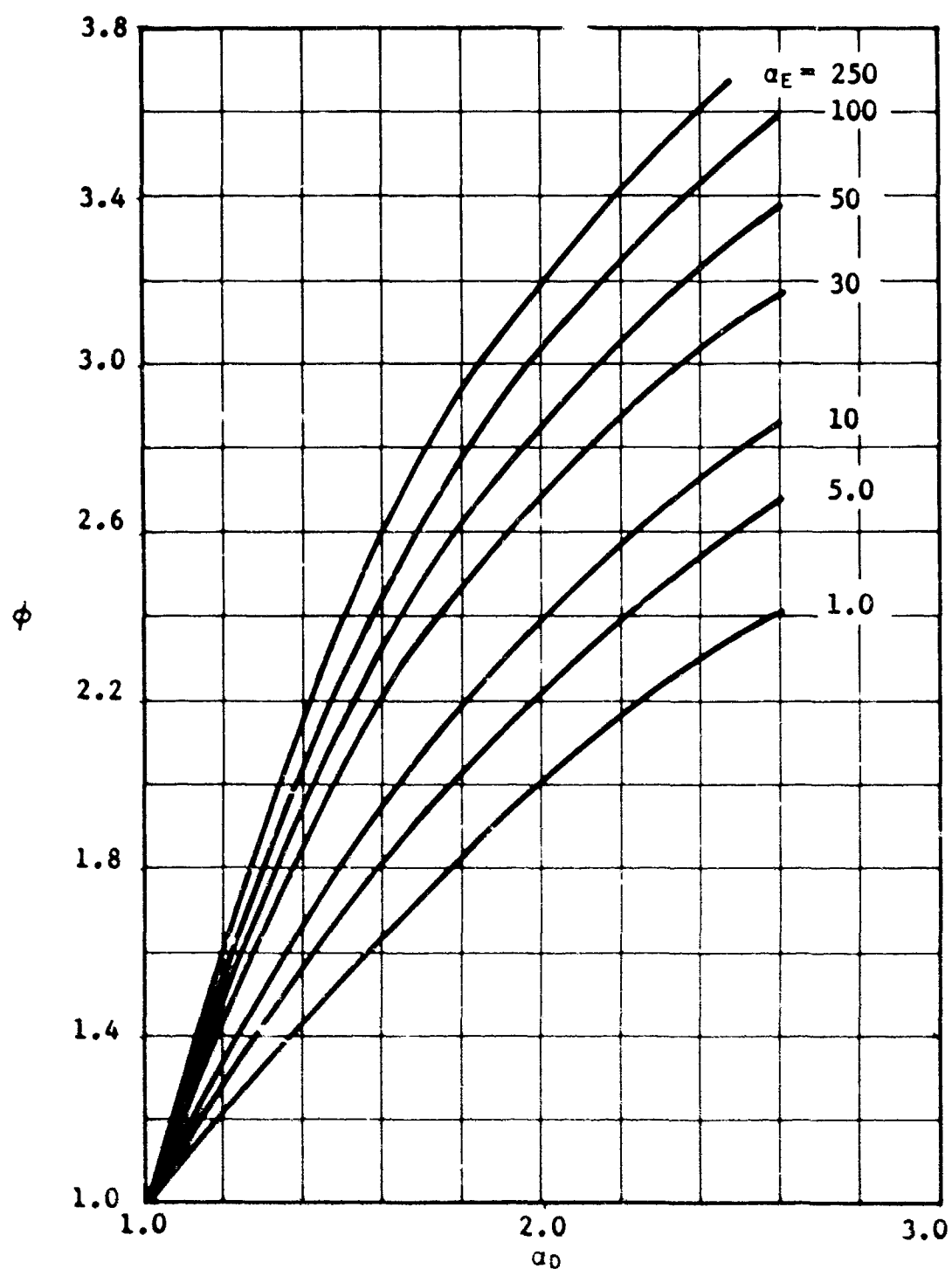
Figure 9. Effect of Diffuser on Thrust Augmentation of a Jet Ejector with Constant Pressure Mixing Chamber (No Forward Speed, No Flow Losses).
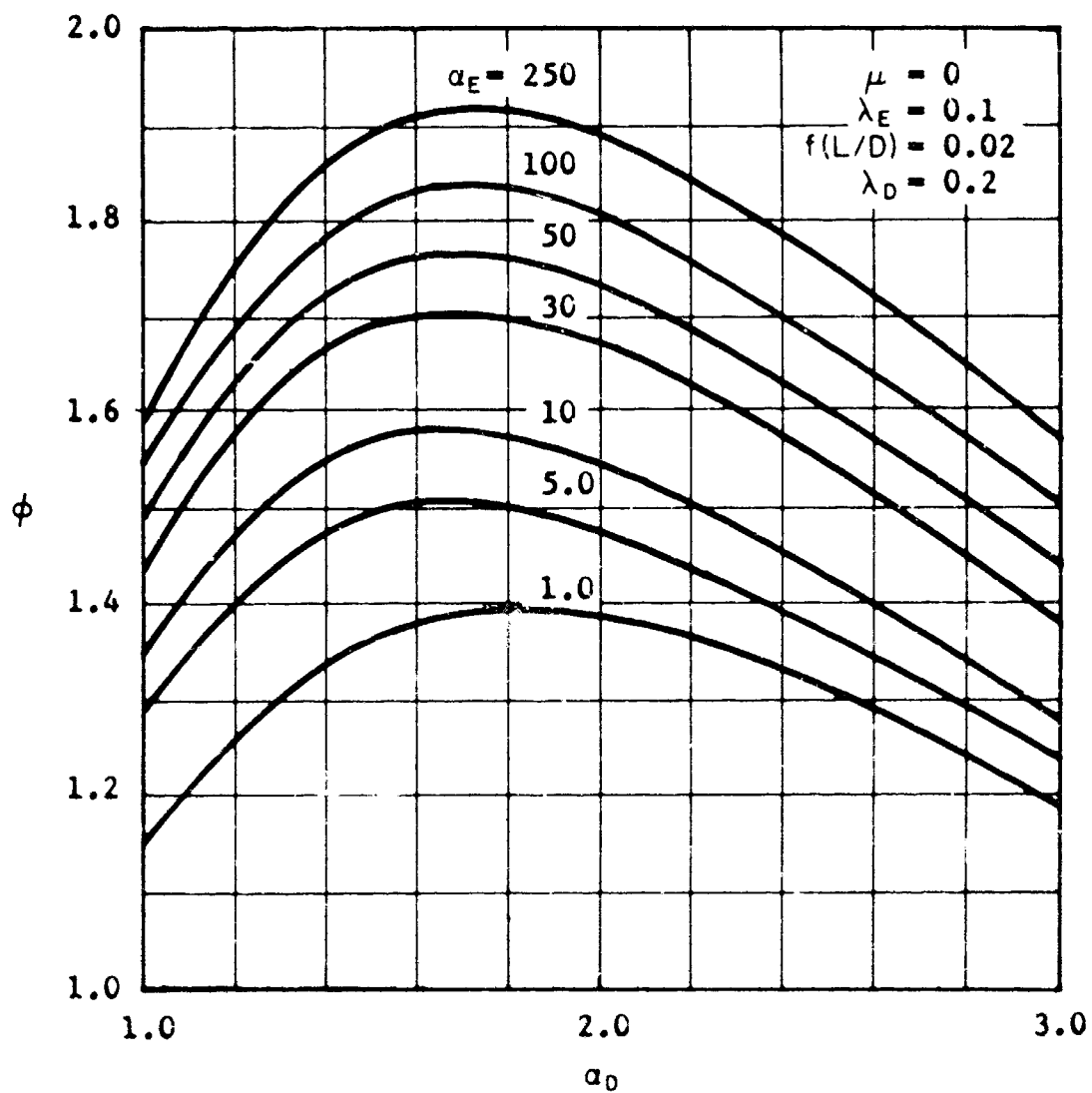
Figure 10. Effect of Diffuser on Thrust Augmentation of a Jet Ejector with Constant Area Mixing Chamber (No Forward Speed, With Typical Flow Losses).

65
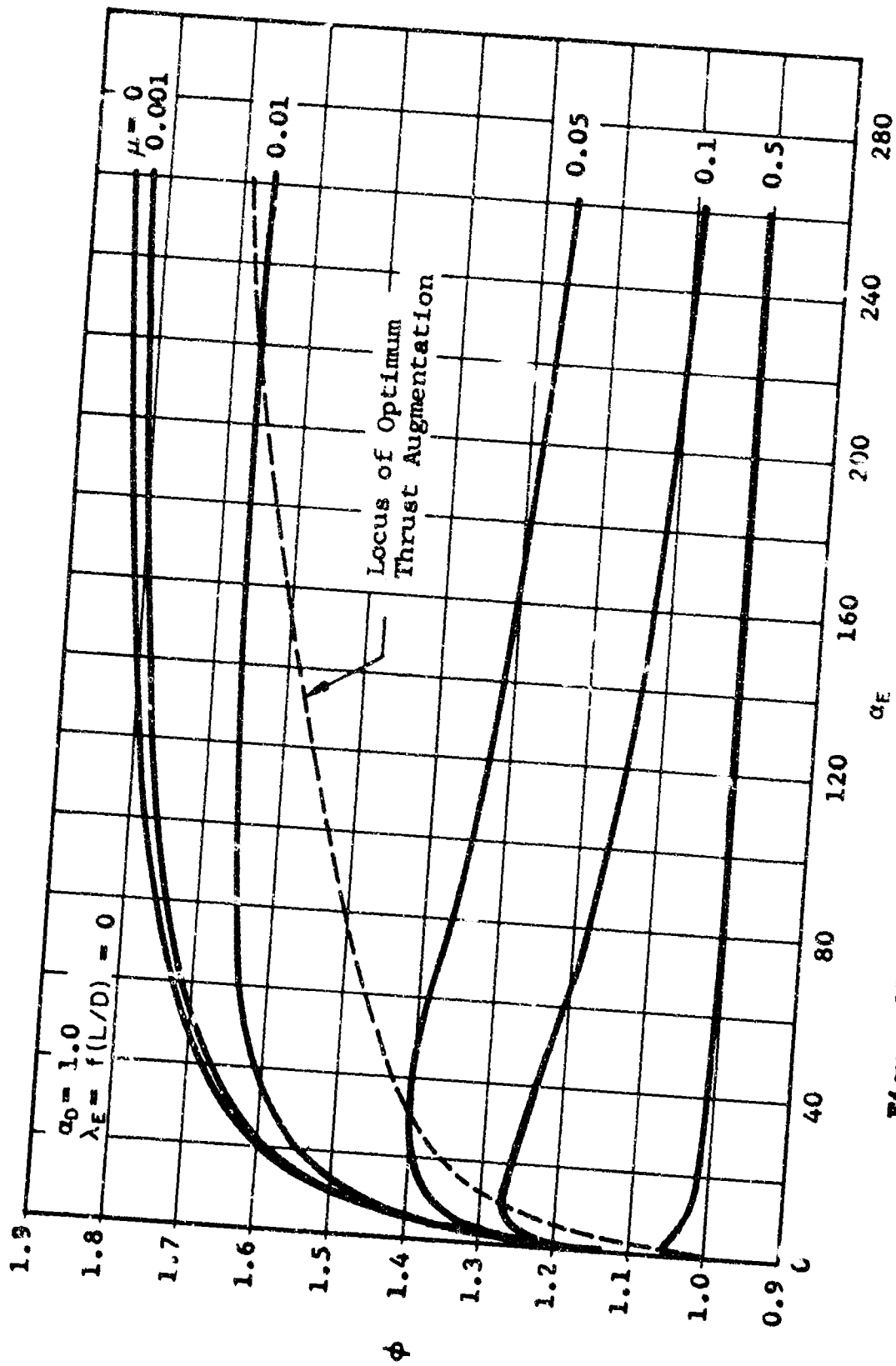
Figure 11. Effect of Forward Speed on Thrust Augmentation Ratio (No Diffuser; No Losses).

66

ratio reaches an optimum value of $1.0 < \phi < 2.0$, and then reduces to unity as the area ratio further increases to infinity. From a physical point of view, the case of infinite α_E corresponds to the condition of primary flow discharged directly into the ambient, resulting in thrust augmentation ratio of unity. This figure also shows the locus of maximum thrust augmentation ratio (dotted line) as a function of α_E for the range of forward speed considered.

Figure 12 shows the effect of forward speed on thrust augmentation ratio ϕ, including typical flow losses for the case of $\alpha_D = 2.0$. Comparing Figures 11 and 12, it can be noted that the effect of forward speed on the reduction of thrust augmentation ratio is more severe when the major flow losses are included. Specifically, for forward speeds greater than $\mu = 0.05$, the thrust augmentation ratio continuously reduces with an increase in α_E and eventually reaches a value of less than 1.0 in the practical design range of α_E.

The above discussion refers to an ejector forward speed along the ejector longitudinal axis, i.e., parallel to jet thrust. If, however, the forward motion is normal to the ejector axis, under idealized flow condition, the ejector performance should not be affected by such motion. In a practical case, the forward motion of an ejector perpendicular to the direction of thrust will result in an asymmetric inflow at the secondary entrance, thereby causing an increase in the secondary entrance head loss $\rangle_{-}$.

D. FLOW COMPRESSIBILITY

The effect of flow compressibility on jet ejector performance is herein determined assuming no forward speed, no diffuser, and no flow losses. Typical computer results for this analysis are presented in Figures 13 through 15. In each of these figures, the thrust augmentation ratio obtained from the idealized incompressible analysis is also shown for the purpose of comparison. It is seen that in general the thrust augmentation ratio ϕ is reduced when the flow compressibility is accounted for.

67
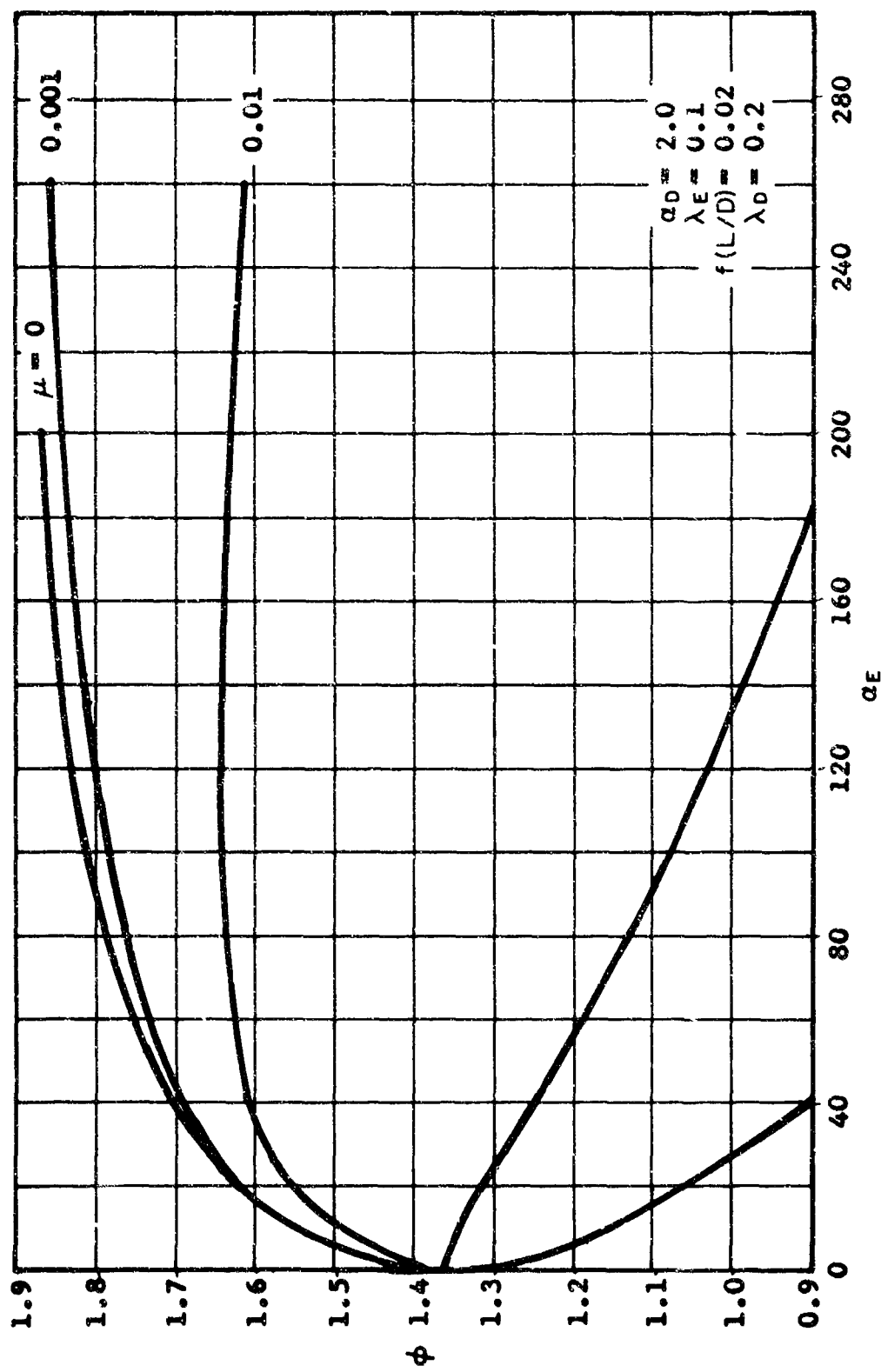
Figure 12. Effect of Forward Speed on Thrust Augmentation
Ratio (with Diffuser; with Typical Losses).

68
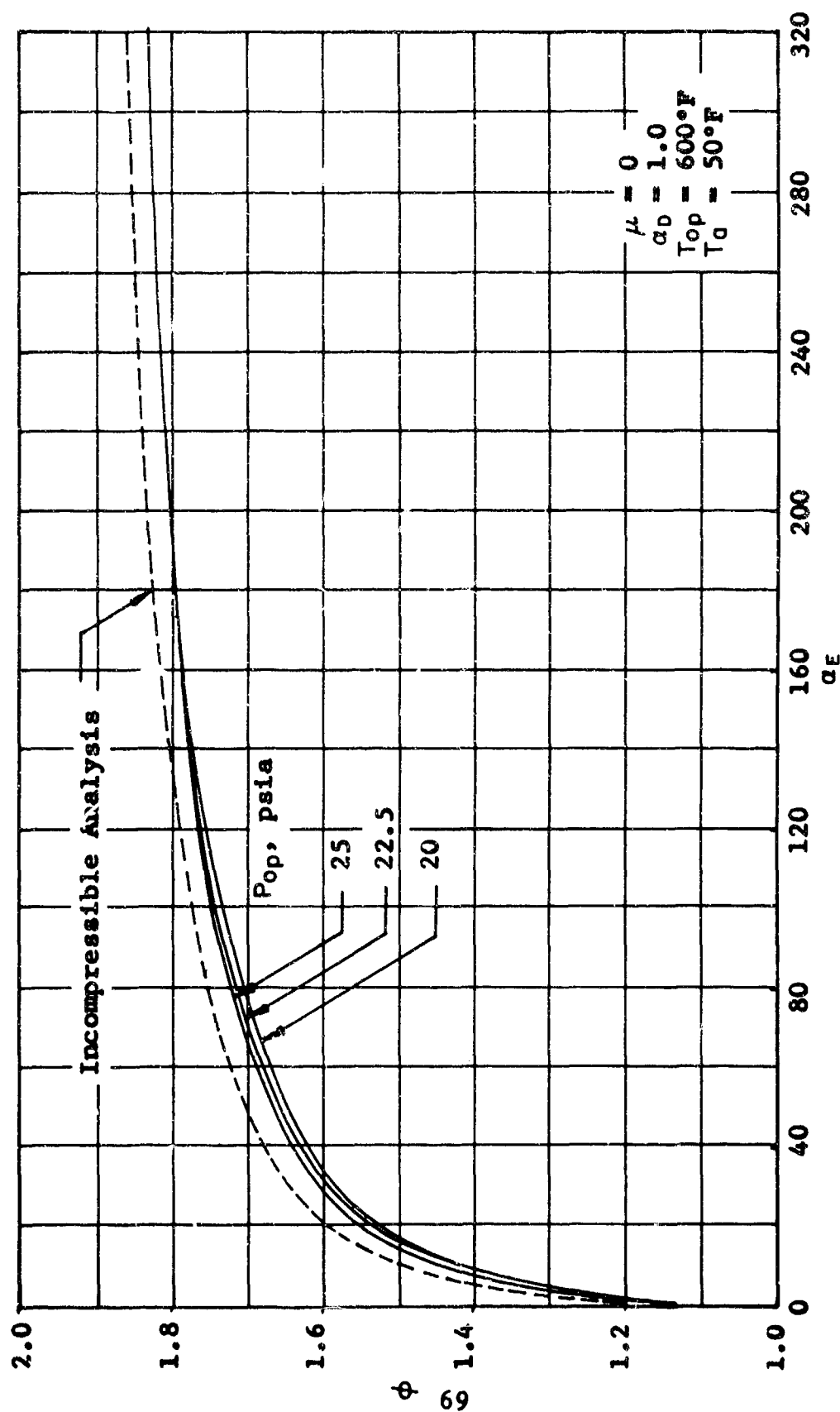
Figure 13. Effect of Primary Stagnation Pressure on Thrust Augmentation Ratio (No Forward Speed; No Diffuser; No Losses).
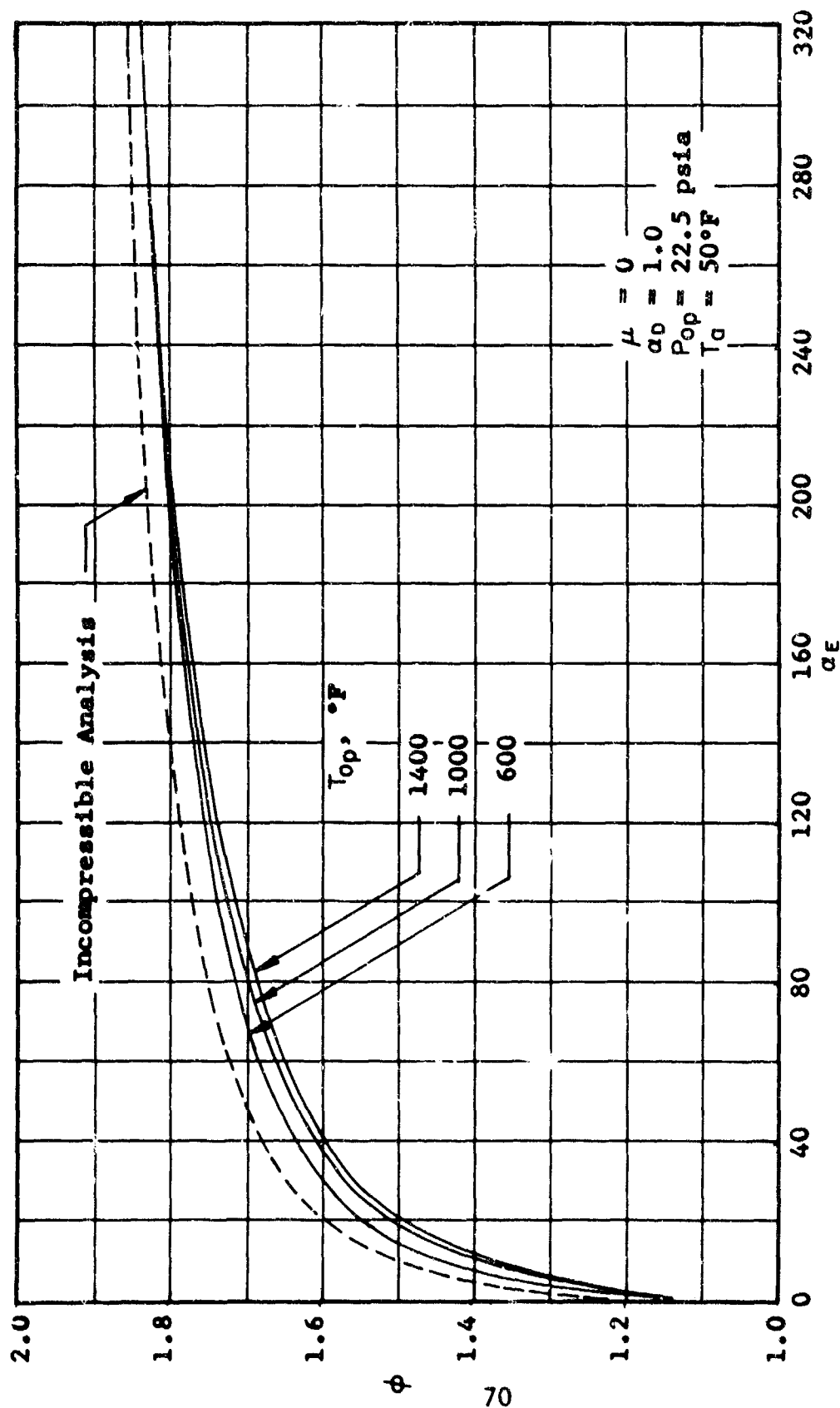
Figure 14. Effect of Primary Stagnation Temperature on Thrust Augmentation Ratio (No Forward Speed; No Diffuser; No Losses).

70
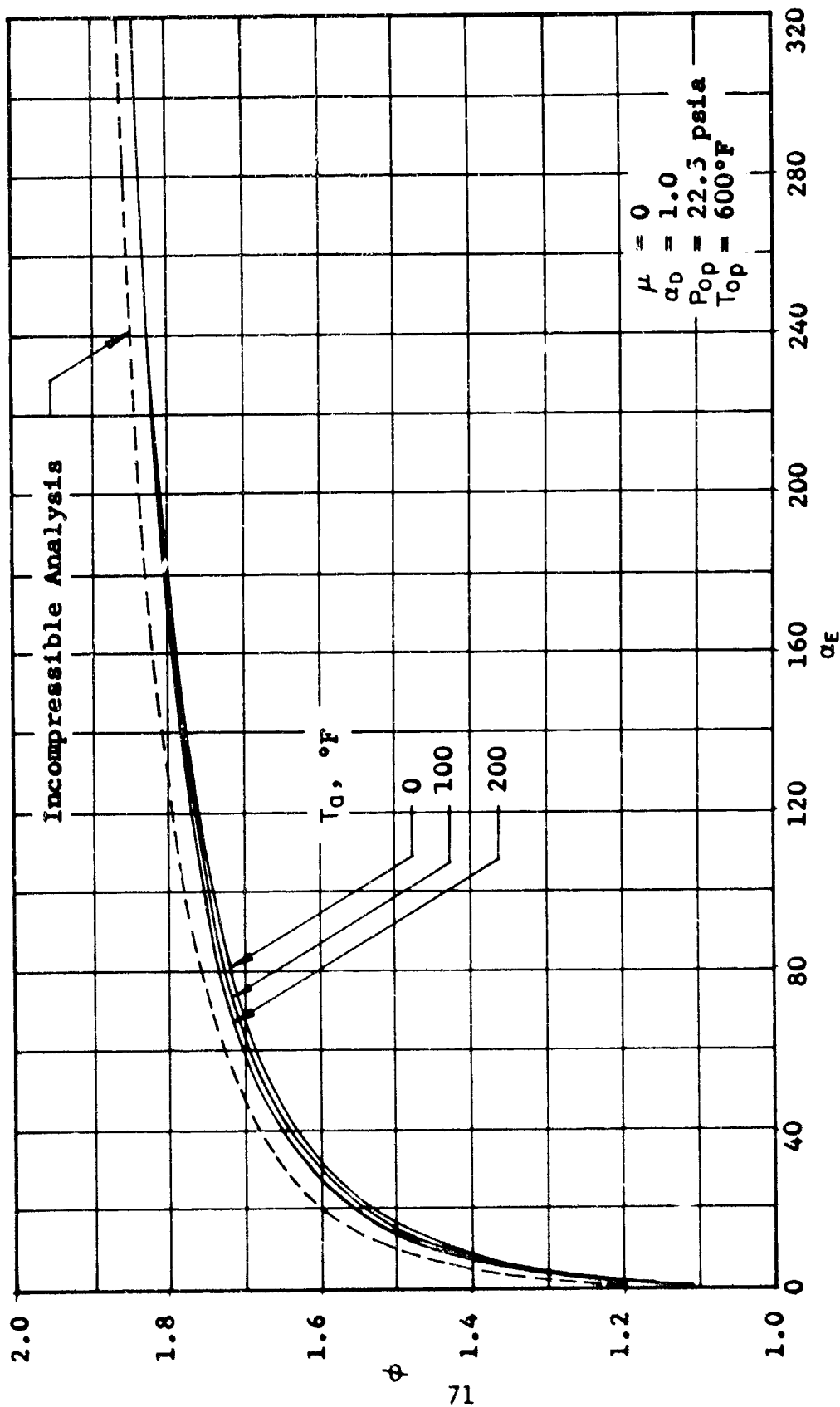
Figure 15. Effect of Ambient Temperature on Thrust Augmentation Ratio (No Forward Speed; No Diffuser; No Losses).

Figure 13 shows that the increase of the primary stagnation pressure P_{0p} from 20 psia to 25 psia results in about 3 percent reduction of the thrust augmentation ratio. P_{0p} is limited to 25 psia in the calculations in order to avoid the choking condition of the nozzle.

The effect of the variation of the primary stagnation temperature T_{0p} is illustrated in Figure 14. The temperature range under consideration is between 600°F and 1400°F. It is seen from this figure that an increase of temperature T_{0p} decreases the thrust augmentation ratio up to a maximum of about 4 percent at area ratios around 10.

The increase in ambient temperature, as shown in Figure 15, results in an increase of thrust augmentation ratio ϕ. This increase, however, does not exceed 2 percent for the range of ambient temperatures raised from 0°F to 200°F and the range of α_E considered.

In general, it can be concluded that although the effect of flow compressibility is to reduce the jet ejector performance as compared to the idealized flow conditions, the effect of the variation of the compressible flow parameters, such as P_{0p}, T_{0p}, and T_0, seems to be of little consequence.

E. MIXING CHAMBER SHAPE

In the present investigation, two mixing chamber shapes have been considered; i.e., the constant area and the constant pressure mixing configurations.

The analysis of the mixing chamber shapes, other than the two investigated, is indeed a very difficult task and has not been successfully attempted by any of the investigators in the past. It appears, however, that due to possible flow separation at the mixing chamber walls, a divergent mixing chamber shape would not be suitable.

Some of the information on the mixing chamber shapes can be obtained by comparing Figures 8 and 9. Examining these figures, it can be seen that for the same secondary-to-primary area ratio α_E and diffuser area ratio α_D, the constant area mixing chamber shape yields superior thrust augmentation performance as compared to that of a constant pressure mixing configuration.

72

F. MIXING CHAMBER LENGTH

The data presented in this report are valid only for the case when the velocity of the mixed flows at the exit of the mixing chamber is uniform. This implies complete mixing of the primary and secondary flows which necessitates adequate mixing chamber length.

The exact mixing process inside a mixing chamber of an ejector is not yet clearly understood. Mikhail (Reference 20) made an attempt to solve the problem; however, the final equations are developed in terms of "mixing length parameters" which vary from case to case and have to be determined empirically.

The experimental data of Reference 15 show that for the mixing chamber length of $L/D = 12$, the velocity distribution at the exit of the mixing chamber is uniform. The value of $L/D = 12$ is not necessarily representative for a variety of jet ejector configurations, since this value will in general depend on the secondary-to-primary area ratio α_E and other geometric parameters.

On the other hand, the experimental data of Reference 2 indicate that an increase in the mixing chamber length beyond the value of $L/D = 5.0$ or 6.0 causes an adverse effect on the jet ejector performance. This implies that the flow losses due to partial mixing, associated with short mixing chamber lengths, are less predominant than the friction losses caused by increasing mixing chamber length to achieve complete mixing. It appears, therefore, that in selecting practical mixing chamber lengths the considerations of the flow losses due to partial mixing may be of secondary importance.

This subject is further discussed later in the text. Also, the charts for estimating mixing chamber lengths of various ejector configurations are presented in Section VII. These charts are based on the fact that the practical mixing chamber length required for optimum ejector performance is less than that required for complete flow mixing. Furthermore, it is assumed that the flow losses due to partial mixing can be neglected provided that the total mixing chamber length for a single nozzle jet ejector is greater than $L/D = 6.0$.

G. DIVERGENCE AND INCLINATION OF NOZZLES

In the previous discussions, it was assumed that, irrespective of the ejector type, the orientation of the primary jet nozzles was along the longitudinal axis of the ejector.

For the case of the central nozzle or multinozzles installed at an angle with the ejector axis, or for the case of the annular nozzle with the jet diverging from the ejector axis, the one-dimensional analysis is considered to be inadequate in predicting the performance of such ejector configurations. The major effect will be the increase of mixing losses due to the flow interaction which is difficult to treat analytically.

In the multiconcentric annular nozzle configuration as developed by Bertin, Reference 10, the divergence of the nozzle seems to be of merit insofar as mixing is concerned. However, no analytical work, besides the usual one-dimensional approach, has been presented by Bertin for the purpose of analyzing the performance of jet ejectors with divergent multiconcentric annular nozzles.

H. EFFECT OF GROUND PROXIMITY

Available test data, e.g., References 21 and 22, indicate that in the ground proximity, the thrust augmentation of an ejector is reduced. This is attributed to the reduction of static pressure prevailing in the flow from the ejector exit. The test data also show that the ejectors operating in parallel, with a common baseplate, yield a higher thrust augmentation than the ejectors operating individually. This is due to the building up of pressure underneath the baseplate where a stagnation condition exists. This effect is similar to what prevails in the case of annular nozzles in ground proximity, for which some theoretical and experimental data are presented in References 23 and 24.

I. NONUNIFORM VELOCITY AT THE SECONDARY ENTRANCE

The practical analysis presented in Section IV as well as other analyses available from the existing literature, is performed with a one-dimensional flow approach. The necessary assumptions, among others, are that the velocities at the secondary entrance and also at the mixing chamber exit are

74

uniform. In practical operations these idealized conditions do not always apply.

For small secondary-to-primary area ratios, the velocity at the secondary entrance is practically uniform. However, as the area ratio α_E increases, the secondary entrance velocity close to the mixing chamber walls becomes much lower than that close to the primary jet.

For very large area ratios (as α_E tends to infinity), the velocity of the secondary flow becomes zero at a finite radial distance from the primary jet. In fact, this condition corresponds to a free jet discharged directly into the ambient, in which case no thrust augmentation is possible. The available analyses, utilizing the assumption of uniform secondary flow velocity, result, however, in a thrust augmentation ratio of 2.0 as α_E tends to infinity.

In the previous section, an attempt is made to account for the radial variation of the local velocity at the secondary entrance. However, this analysis is based on a semi-empirical approach requiring furhter experimental verification.

J. INCOMPLETE MIXING

The effect of incomplete (partial) mixing of the primary and secondary flows at the exit of the mixing chamber has also been investigated. As discussed previously, the incomplete mixing will exist due to the insufficient length of the mixing chamber, thereby resulting in a nonuniform velocity profile at the exit of the mixing chamber.

The difficulties of analyzing partial mixing are in principle similar to those associated with nonuniform velocity at the secondary entrance discussed above. In this case, however, even if the velocity profile at the exit of the mixing chamber 's known or assumed, the corresponding variation of the static pressure distribution cannot be analytically determined.

Forstall and Shapiro (Reference 25) indicate that the velocity profile at the exit of the mixing chamber can be quite accurately represented by a cosine or three-halves

75

power curve. However, information on the static pressure
distribution at the exit of the mixing chamber and the mass
flow rate of the partially mixed flow is not available.
Thus, in order to predict reliably the effects of the
incomplete (partial) mixing, an experimental investigation is
necessary to obtain the pertinent data on pressure and
velocity distributions at the exit of the mixing chamber.

K. MIXING LOSSES IN THE MIXING CHAMBER

The mixing losses in the mixing chamber cannot be considered
as an additional external force which could be readily
introduced in the momentum equation. One method of
accounting for the mixing losses is to assume a mixing
efficiency factor (η_M) in the flow momentum considerations.
However, there is no information available for determining
this mixing efficiency factor.

L. FLOW VISCOSITY

A real fluid flow is generally treated as an inviscid flow,
except that at the locations close to the walls a boundary
layer effect is taken into consideration. The flow viscosity
effects give rise to friction drag which in turn reduces the
jet ejector thrust. In the present investigation, the losses
due to the friction drag along the mixing chamber walls are
included in the friction factor f, which appears in the
momentum equation.

For the diffuser section, the losses due to friction drag and
flow separation are included in the diffuser loss factor λ_D .

M. HEAT CONDUCTION LOSSES

In the practical analysis (compressible flow), the heat
conduction losses will affect the energy equations presented
in Section IV. However, the information pertaining to the
rate of heat conduction which varies with ejector geometry,
conductivity of mixing chamber walls, and the operating
conditions of the ejector system is inadequate for reasonable
evaluation.

76

Furthermore, due to the heat conduction losses, the ejector flows become neither isentropic nor adiabatic, resulting in an additional difficulty in analyzing the flow process.

In general, however, the mixing chamber is usually not very long and the secondary flow is almost under ambient conditions, so that heat conduction losses, if any, through the mixing chamber and diffuser walls are not significant and can be neglected without materially affecting the accuracy of the analysis.

N. EFFECT OF SPECIFIC HEAT RATIO γ

Using the computer program, Appendix I, an investigation was performed to determine the effects of the specific heat ratio γ on jet ejector performance. It was found, however, that for a range of γ from 1.25 to 1.4, the thrust augmentation ratio is practically unchanged (less than 0.1 percent).

It appears, therefore, that the effect of the specific heat ratio can be neglected in the practical jet ejector analysis.

VI. CORRELATION WITH EXPERIMENTAL DATA

Available experimental data which are suitable for correlation with the results of the present analysis are rather limited. Those data which contain information on thrust augmentation do not, in general, furnish sufficient design and construction details which could be used to determine the various flow loss factors. Consequently, for some of the jet ejector configurations, these loss factors were determined by using good engineering judgement.

Specifically, the friction loss factor $f(L/D)$ was determined assuming $f = 0.003$ and using the test values of (L/D) provided in most cases. Reference 26 was used to determine the overall diffuser loss factor λ_0.

As pointed out previously, it is not easy to determine the secondary entrance flow loss factor λ_E. It appears that the intake geometries of the various ejector configurations tested are of either round or bellmouth shape, for which, according to the results of Reference 27, the entrance loss factor is about 0.1. Thus, in the absence of better information applicable to each specific configuration, λ_E has been taken as 0.1 for the present correlation.

The correlation of the test data with the theoretically predicted results utilizing the loss factors described above is performed in tabular form as shown below. The reason for the selection of this method of presentation is the fact that the test data obtained for a variety of jet ejector configurations are unsuitable for graphical comparison.

The correlations are performed for the following jet ejector configurations:

A. SINGLE CENTRAL NOZZLE CONFIGURATIONS

The following references contain the test data obtained for a single central nozzle configuration:

(i) Reference 2 presents the test data for the case of an ejector without a diffuser. The correlation of these data with theoretically predicted values is given in Table I.

78

TABLE I

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 2,
SINGLE NOZZLE EJECTOR WITH NO DIFFUSER

α_E	ϕ Theory	ϕ Test
6.0	1.30	1.25
11.0	1.36	1.29
24.0	1.42	1.34
29.0	1.44	1.38
59.0	1.51	1.43

The calculated values are based on the following loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.02$$

$$\lambda_D = 0 \text{ (No diffuser)}$$

The above table indicates a satisfactory correlation between the theoretical and experimental results.

(ii) The test data obtained from Reference 15 are for a central nozzle configuration without a diffuser. The correlation of the test results with the theoretically predicted values is given in Table II.

79

TABLE II

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 15, SINGLE NOZZLE EJECTOR WITH NO DIFFUSER

α_E	ϕ Theory	ϕ Test
3.0	1.22	1.03
10.7	1.36	1.20
15.0	1.37	1.26
28.7	1.44	1.40
46.0	1.48	1.48
104.5	1.55	1.50

The theoretically predicted values are based on the following flow loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.02$$

$$\lambda_D = 0 \text{ (No diffuser)}$$

The comparatively poorer correlation at small area ratios is believed to be due to the higher secondary entrance losses. Also, the test data indicate that with the increase of the area ratio α_E from 46.0 to 104.5 (more than double), the increase in augmentation ratio is only about 1 percent. On the other hand, from the theoretically predicted results, the corresponding increase in thrust augmentation is about 5 percent. This can be attributed to the effect of the nonuniform velocity profile at the secondary entrance (not accounted for in the theory). This effect becomes more important at high secondary-to-primary area ratios.

80

(iii) Reference 16 quotes the following test data for a constant area mixing ejector without diffuser:

α_E	Test
129.5	1.95
339.0	2.11
329.0	2.21
369.0	2.21

The thrust augmentation ratios shown above are either close to or higher than the maximum possible values which can be obtained from the idealized, one-dimensional incompressible analysis, viz., 2.0. Furthermore, on account of the large area ratios of $\alpha_E >$ 130, the secondary velocity at the entrance plane would no longer maintain its uniformity; consequently, it would be doubtful whether the maximum augmentation ratio of 2.0 could be reached at all even if all the losses were neglected. The original work (Reference 28) does not furnish any usable information to justify the unusually high performance claimed for the simple central nozzle type ejector as illustrated therein.

(iv) Reference 29 presents the test results for the ejector with and without a diffuser. The correlation of these data with the theoretically predicted values is given in Table III.

TABLE III

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 29,
SINGLE NOZZLE EJECTOR WITH AND WITHOUT DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
26.36	1.00	1.45	1.37
7.54	1.00	1.34	1.28
7.54	2.49	1.41	1.23
19.55	1.00	1.43	1.35
5.42	1.00	1.29	1.27
5.42	2.49	1.39	1.29

The test data of Table III indicate that for constant area ratios (α_E= 7.54 or α_E = 5.42), the addition of a diffuser with α_D = 2.49 results in a reduction of thrust augmentation ratio ϕ . This reflects a poor diffuser efficiency (high losses) of the jet ejector configuration tested.

(v) The tests of Reference 30 were performed on a two-dimensional model with no diffuser. A comparison of the test data with the theoretically predicted results is given in Table IV.

TABLE IV

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 30,
SINGLE NOZZLE EJECTOR WITH NO DIFFUSER

α_E	ϕ Theory	ϕ Test
3.24	1.16	1.08
7.13	1.24	1.16
11.5	1.27	1.23
19.0	1.31	1.30
23.0	1.32	1.30
27.0	1.33	1.30
31.0	1.34	1.28

The predicted values are obtained by taking $\lambda_E = 0.1$ and $f(L/D) = 0.05$. A higher friction loss factor is used in this case, as compared with the above configurations, in view of the fact that due to the larger wall area in the two-dimensional model, the friction losses are undoubtedly higher, especially at low secondary-to-primary area ratios.

The results presented in Table IV show a good correlation between the theoretical and experimental values.

(vi) Reference 31 presents the test data on the effect of total primary stagnation pressure ratio on thrust augmentation. The test conditions are as follows:

$$T_{O_p} = 300°K = 510°R \ (50°F)$$

$$T_a = 283°K = 478°R \ (18°F)$$

$$\alpha_E = 50.0$$

$$L/D = 5.0$$

The test data of Reference 31 indicate that the thrust augmentation ratio ϕ decreases gradually from 1.24 to 1.22 as P_{O_p}/P_a increases from 1.4 to 1.8. From the analysis, the thrust augmentation ratio is obtained as 1.25 by taking $f(L/D) = 0.025$, as suggested by the paper.

(vii) Reference 32 shows that at an area ratio $\alpha_E = 2.33$, the central nozzle ejector without diffuser ($L/D = 6$) has its thrust augmentation ratio ϕ decreasing from 1.195 to 1.165 as the primary pressure ratio P_{O_p}/P_a increases from 1.4 to 1.8. The corresponding theoretical value based on loss factors of $f(L/D) = 0.02$ and $\lambda_E = 0.1$ is 1.20.

B. MULTIPLE NOZZLE CONFIGURATIONS

The test data for the multiple nozzle configurations are obtained from the following references:

(1) The test data reported in Reference 13 pertain to an ejector configuration with multiple nozzles, a rectangular mixing chamber, and a diffuser with lemniscate contour. Table V shows the correlation of the test data with the theory.

TABLE V

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 13,
MULTIPLE NOZZLE EJECTOR WITH RECTANGULAR
MIXING CHAMBER AND A DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
35.5	3.11	1.38	1.55
55.5	2.73	1.54	1.66
74.4	2.36	1.70	1.79
135.5	1.36	1.79	1.78

The above table shows a satisfactory correlation
between the test results and the corresponding
theoretical values. This correlation is based
on the following flow loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.02$$

$$\lambda_D = 0.2$$

(ii) The test data of Reference 18 and the predicted
values are given in Table VI.

TABLE VI

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 18,
MULTIPLE NOZZLES ARRANGED IN A CIRCLE

α_E	α_D	ϕ Theory	ϕ Test
14.37	1.8	1.71	1.72
31.4	2.2	1.75	1.71
51.0	2.47	1.73	1.90

The test model used has multiple nozzles arranged in a circle. The mixing chamber is slightly convergent (the exit area is 8 percent less than the entrance area), which does not assu e constant pressure at the walls. The predicted values shown in Table VI are obtained using the following loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.01$$

$$\lambda_D = 0.2$$

It is seen that for the first two configurations, correlation is satisfactory, whereas for the last one the test result is 10 percent higher than that theoretically predicted.

(iii) Table VII shows the effect of diffuser area ratio α_D on thrust augmentation ϕ for constant secondary-to-primary area ratio $\alpha_E = 12.0$. The test data were extracted from Reference 21 and are applicable to a four-row nozzle configuration.

86

TABLE VII

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 21,
FOUR-ROW NOZZLE CONFIGURATION WITH VARIABLE DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
12.0	1.00	1.37	1.35
12.0	1.19	1.48	1.45
12.0	1.38	1.56	1.55
12.0	1.58	1.59	1.61
12.0	1.77	1.59	1.64
12.0	2.16	1.53	1.57

Table VII shows a good correlation between experimental and theoretical results, indicating that the best diffuser area ratio α_D for optimum thrust augmentation ratio is between $\alpha_D = 1.5$ and 2.0. Similar conclusion is reported in Section V, where the effects of a diffuser are discussed.

(iv) The configuration referred to in Reference 33 consists of a rectangular parallel-wall mixing chamber with a diffuser and multiple primary nozzles. The comparison of the predicted thrust augmentation ratios with the corresponding measured values is presented in Table VIII.

87

TABLE VIII

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 33, SINGLE AND THREE-ROW NOZZLES, RECTANGULAR MIXING CHAMBER WITH DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test Single-Row Nozzle	ϕ Test Three-Row Nozzle
6.6	1.23	1.44	1.27	1.36
12.0	1.38	1.56	1.37	1.50
29.3	1.61	1.70	1.45	1.83
51.0	1.73	1.77	1.56	1.89

The third column in Table VIII represents predicted values based on the following values of flow loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0.02$$

$$\lambda_D = 0.2$$

It is seen that for the first two area ratios ($\alpha_E = 6.6$ and 12.0), the predicted values are higher than the test data for both configurations, viz., single row of nozzles and three rows of nozzles. This is believed to be chiefly due to an underestimation of the total head loss factor at the secondary entrance λ_E.

For the other two area ratios ($\alpha_E = 29.3$ and 51.0), the predicted values are higher than the test data for the single-row nozzle configuration but lower than those for the three-row nozzle configuration.

C. ANNULAR NOZZLE CONFIGURATIONS

Finally, for the annular nozzle configuration, the following
test data are utilized:

(i) The tests as reported in Reference 22 were
performed with single annular nozzle configurations.
For the model with a straight mixing chamber
(no diffuser), the results are shown in Table IX.

TABLE IX

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 22,
ANNULAR NOZZLE EJECTOR WITH NO DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
13	1.0	1.41	1.29
17	1.0	1.44	1.38
22	1.0	1.46	1.42

The predicted values are based on the following
flow losses:

$$\lambda_F = 0.1$$

$$f(L/D) = 0.01$$

$$\lambda_D = 0 \text{ (No diffuser)}$$

The corresponding results for a divergent mixing
chamber-diffuser (exit area approximately double
the entrance area) are shown in Table X.

TABLE X

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 22,
ANNULAR NOZZLE EJECTOR WITH DIVERGENT MIXING CHAMBER-DIFFUSER

α_E	ϕ Theory	ϕ Test
8	1.78	1.48
9	1.79	1.53
11	1.81	1.56

The theoretically predicted values for the thrust augmentation ratio ϕ have been obtained for a diffuser area ratio of $\alpha_D = 2.0$ with the following loss factors:

$$\lambda_E = 0.1$$

$$f(1/D) = 0 \text{ (No mixing chamber)}$$

$$\lambda_D = 0.2$$

The large discrepancy between the actual performance and the predicted results is attributed to the incomplete mixing that can be expected at the exit of a diverging mixing chamber-diffuser of relatively small length.

Presented in Reference 22 are also some two-dimensional and three-dimensional test results for the annular jet ejectors.

The correlation of theory with the two-dimensional results is shown in Table XI.

90

TABLE XI

CORRELATION OF THEORY WITH TWO-DIMENSIONAL DATA
OF REFERENCE 22, ANNULAR NOZZLE EJECTOR
WITH DIVERGENT MIXING CHAMBER-DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
9.0	2.0	1.80	1.30
11.5	2.0	1.82	1.50
14.0	2.0	1.84	1.43

The predicted values are obtained from the
practical analysis with the following flow loss
factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0 \text{ (No mixing chamber)}$$

$$\lambda_D = 0.2$$

As can be seen from Table XI, the test results are
appreciably lower than the corresponding predicted
values. This difference in the results can be
attributed to the following factors:

(a) The tests were performed for the ejector
configuration having a small length-to-
diameter ratio (L/D = 3.0). At this ratio
of L/D, it can be expected that the
mixing at the exit of the diffuser will
not be complete, contrary to the complete
mixing assumption in the theory.

(b) Since the primary jet is very close to the
diffuser walls, it is expected that the
friction loss in the diffuser will be
increased as compared to conventional

91

central nozzle configurations. This
increase in the skin friction in the
diffuser could be accounted for by
increasing the diffuser loss factor λ_D .

The correlation of three-dimensional test data of
Reference 22 with the theoretically predicted
results is shown in Table XII.

TABLE XII

CORRELATION OF THEORY WITH THREE-DIMENSIONAL DATA
OF REFERENCE 22, ANNULAR NOZZLE EJECTOR
WITH DIVERGENT MIXING CHAMBER-DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
20.8	1.45	1.66	1.34
20.8	1.63	1.69	1.40
20.8	1.85	1.68	1.47
20.8	1.94	1.66	1.49

The predicted results are based on the same loss
factors as the two-dimensional results. Also in
this correlation, the three-dimensional test data
are lower than the corresponding predicted values
for the same reasons as explained above in the
two-dimensional correlation.

(ii) Table XIII shows the correlation of the test data
as presented in Reference 34 with the theoretically
predicted values.

92

TABLE XIII

CORRELATION OF THEORY WITH TEST DATA OF REFERENCE 34,
THREE-RING ANNULAR NOZZLE EJECTOR WITH DIFFUSER

α_E	α_D	ϕ Theory	ϕ Test
44.0	1.58		1.93
44.0	1.90	2.02	2.16
44.0	2.30		2.32

The test data are for the configuration with a three-ring annular nozzle. The theoretically predicted value of ϕ = 2.02 applies to α_E = 44.0 and α_D = 2.0 and is based on the following loss factors:

$$\lambda_E = 0.1$$

$$f(L/D) = 0 \text{ (No mixing chamber)}$$

$$\lambda_D = 0.2$$

It can be noted that the theoretically predicted value is lower than the test data claimed.

VII. RAPID METHOD FOR EJECTOR PERFORMANCE PREDICTION

Presented in this section is a compilation of charts for rapid prediction of jet ejector performance. The numerical results used in these charts were obtained by solving the theoretical flow equations presented in Section IV.

A. IDEALIZED ANALYSIS

The idealized flow equations were computed manually for both constant area and constant pressure mixing. The corresponding numerical results are herein presented in Figures 16 and 17, which show the variation of the idealized thrust augmentation ratio ϕ as a function of secondary-to-primary area ratio α_E for a series of constant values of diffuser area ratio α_D.

B. PRACTICAL ANALYSIS

The practical analysis was solved with the aid of an IBM 360 digital computer utilizing FORTRAN IV machine language. In this case, two computer programs were developed, one for the incompressible analysis including the effects of major flow losses, diffuser, and forward speed, and the other for the compressible analysis including only the effects of flow compressibility. A detailed description of the programs including flow diagrams and typical computer outputs is presented in Appendix I. The final computer results obtained for static conditions are herein presented as nomographs, Figures 18 through 22.

These charts represent an effective analytical tool in predicting jet ejector performance including flow losses and the effects of flow compressibility and are suitable for use in the preliminary design of jet ejectors. One of the advantages of the selected method of presentation is the fact that a wide range of practical jet ejector operating conditions as well as a variety of flow losses are condensed in a total of five nomographs. Four of these charts, Figures 18 through 21, contain the computer results for the

94
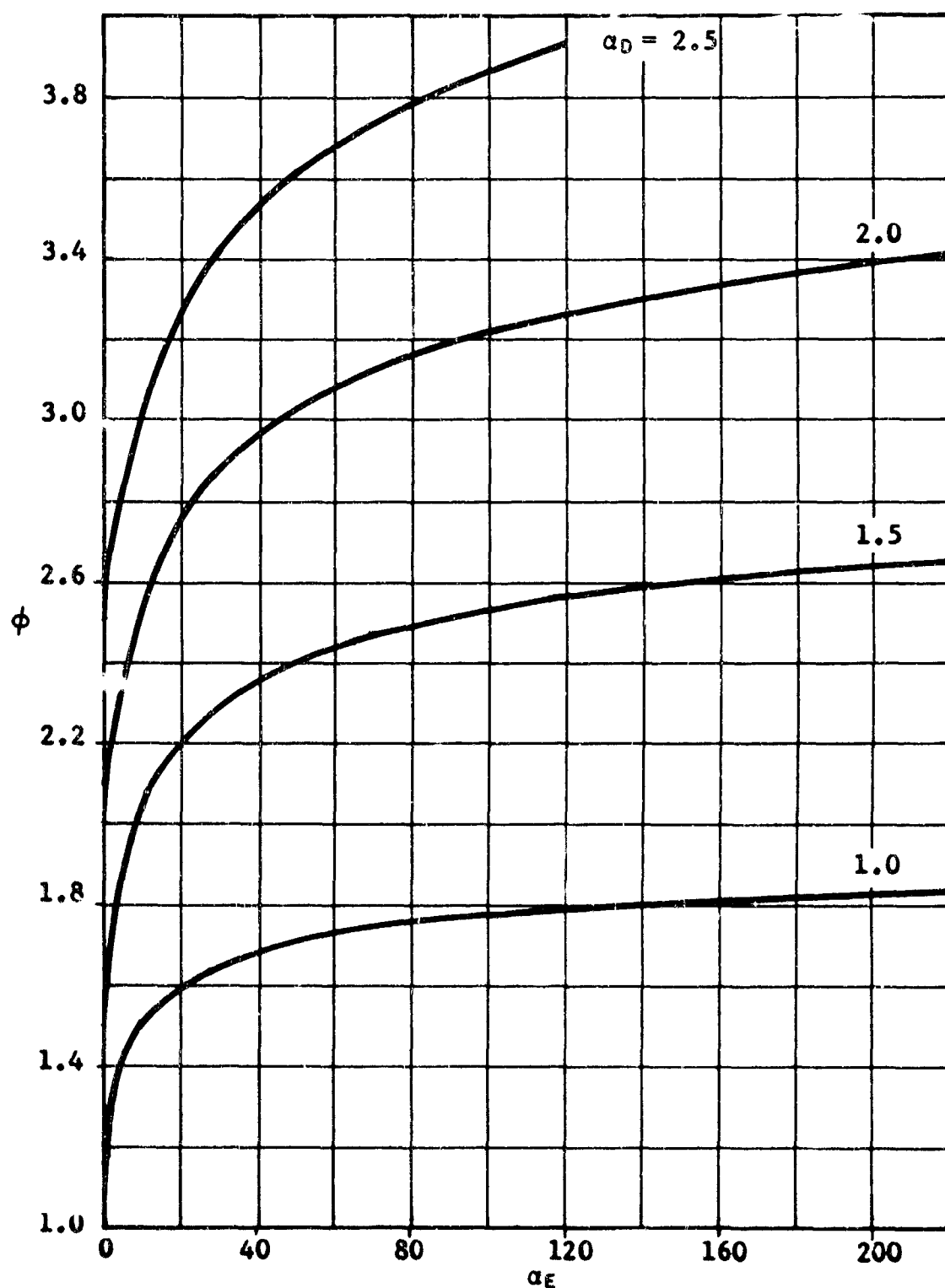
Figure 16. Thrust Augmentation Ratio -
Idealized Analysis for Constant Area
Mixing.

95
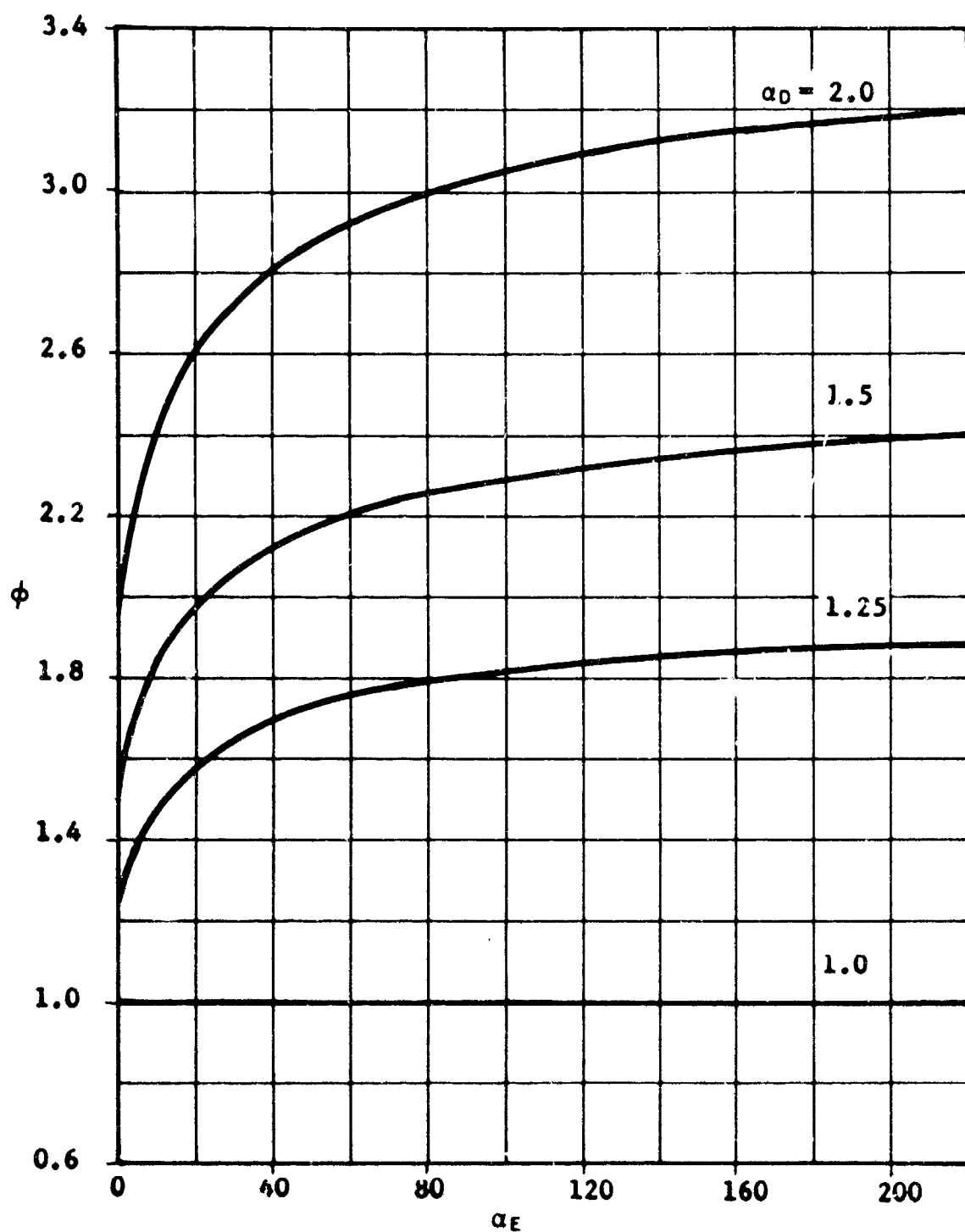
Figure 17. Thrust Augmentation Ratio -
Idealized Analysis for Constant Pressure
Mixing.

96
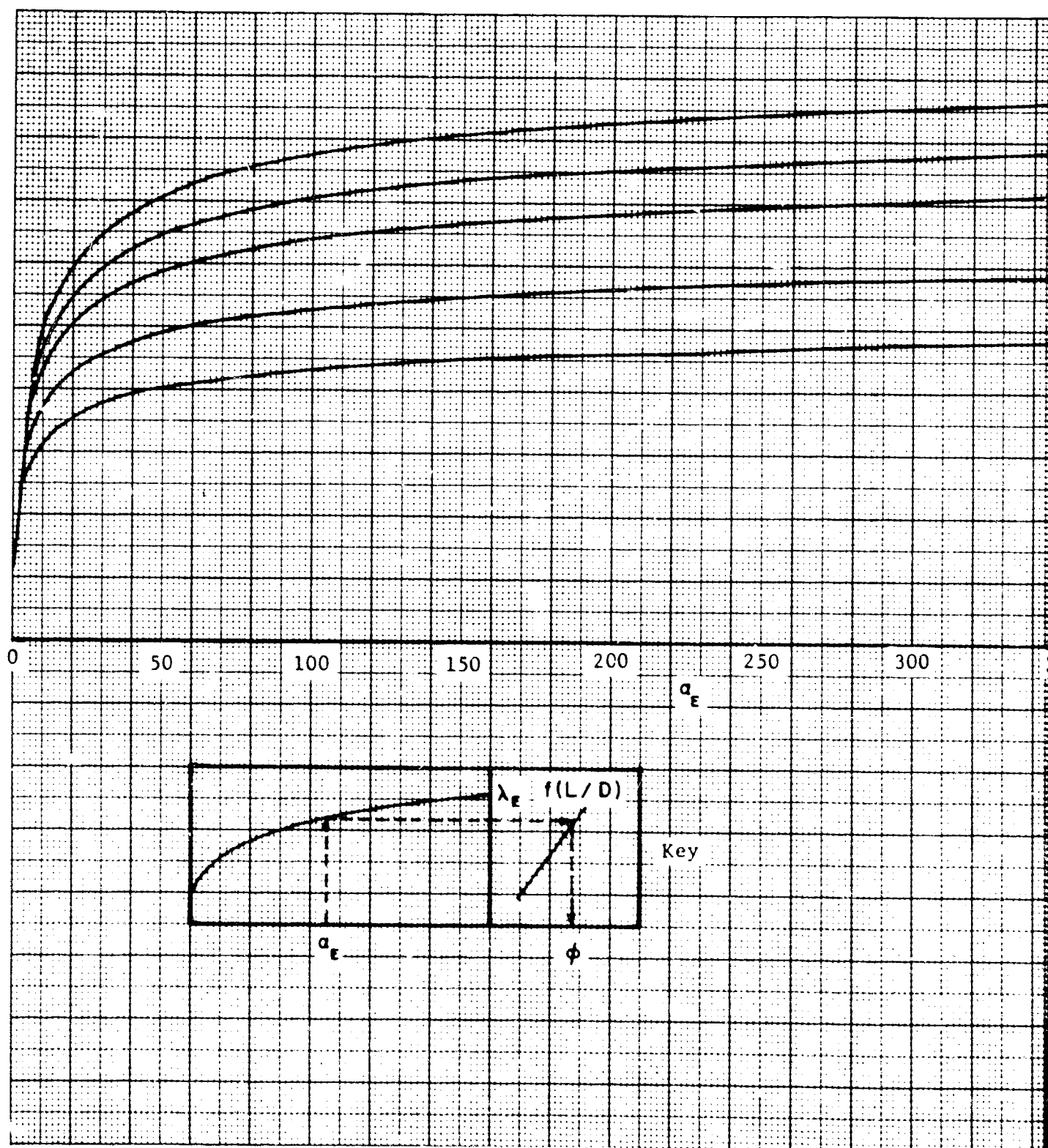
Figure 18. Nomograph for Thrust Augmentation Ratio - Incompressible Flow Analysis Including Flow Losses $(a_0 = 1.0; \mu = 0)$

97
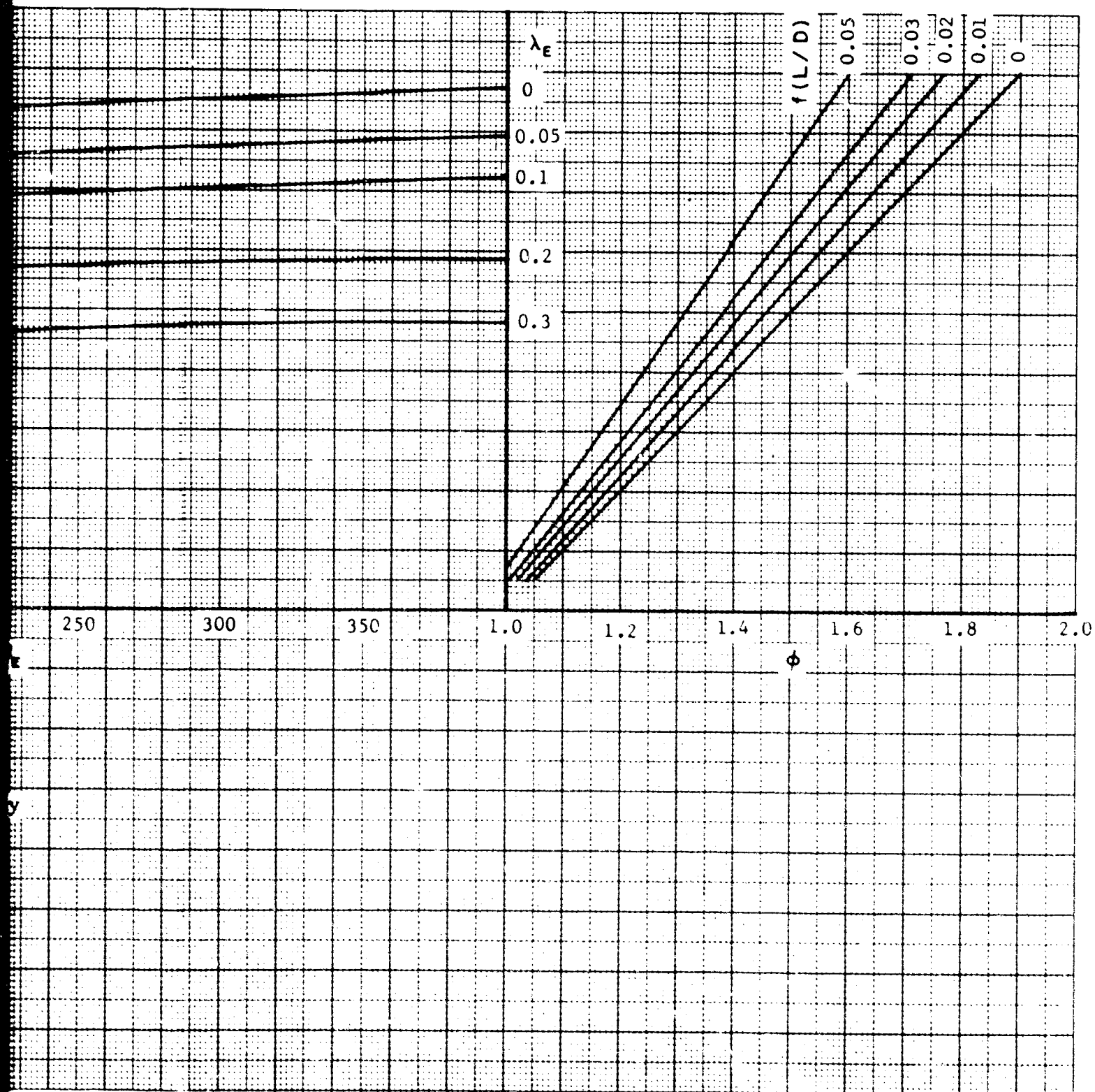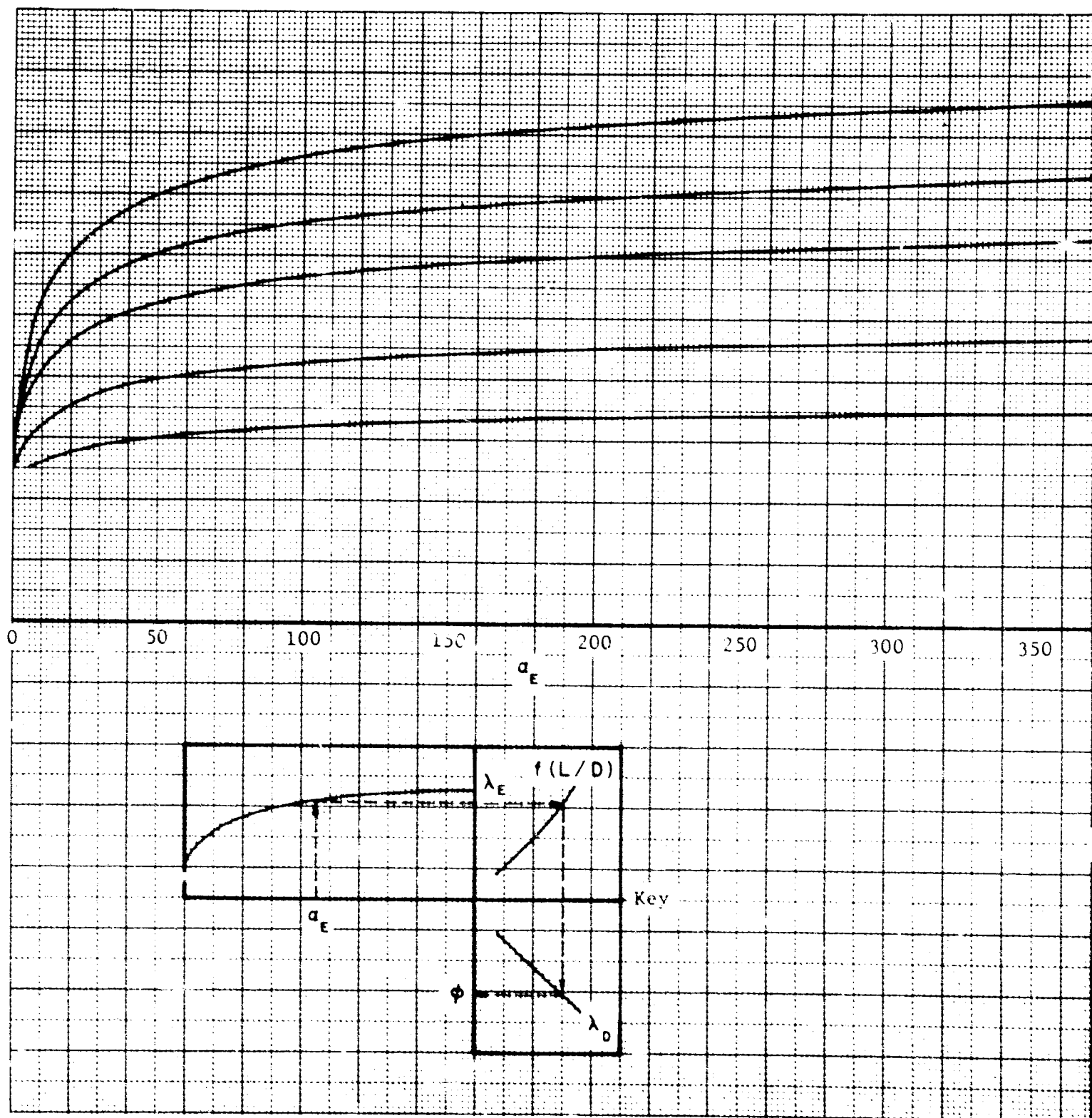
Figure 19. Nomograph for Thrust Augmentation Ratio - Incompressible
Flow Analysis Including Flow Losses ($a_D = 1.5; \mu = 0$)

99

H

Key
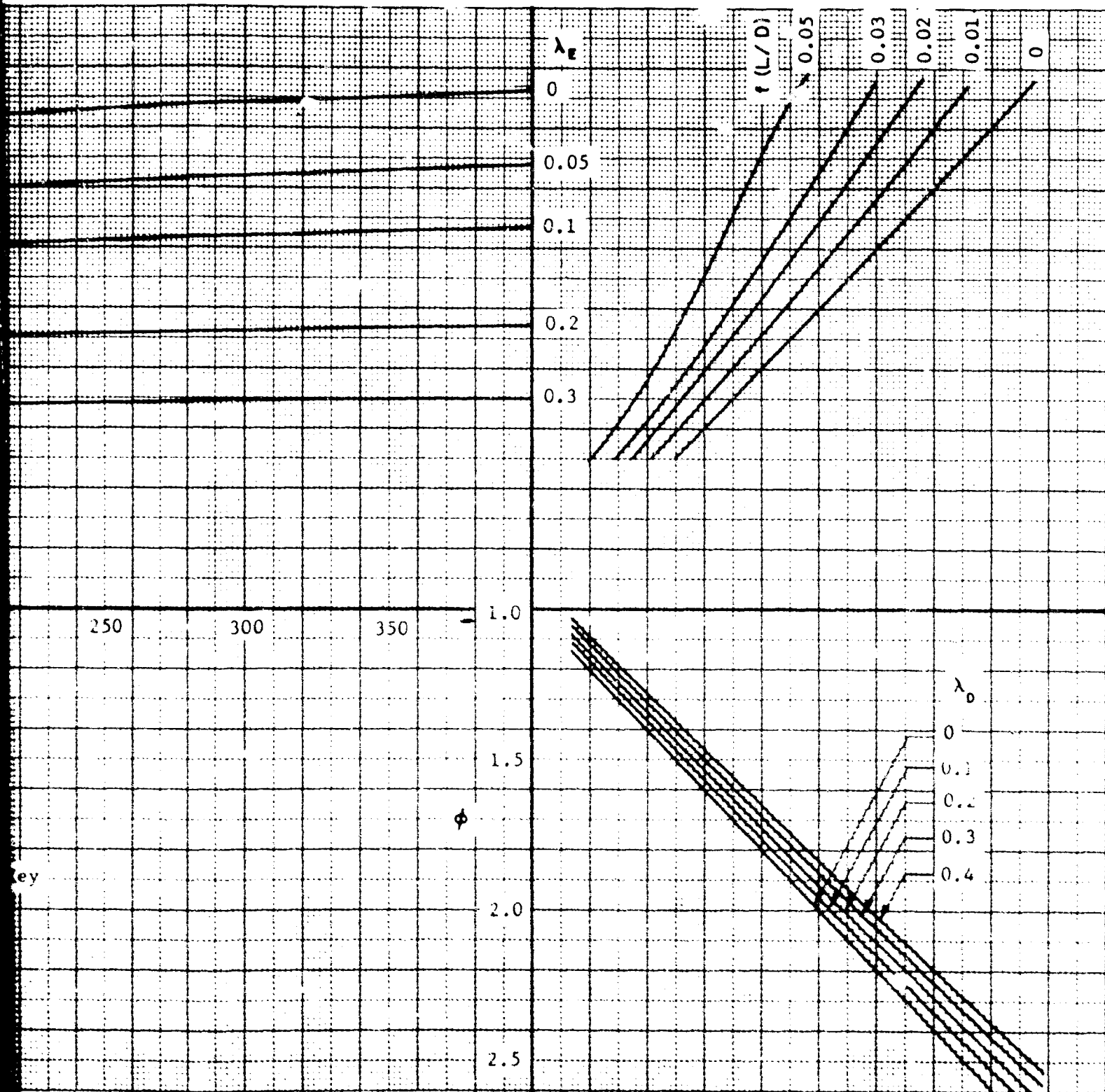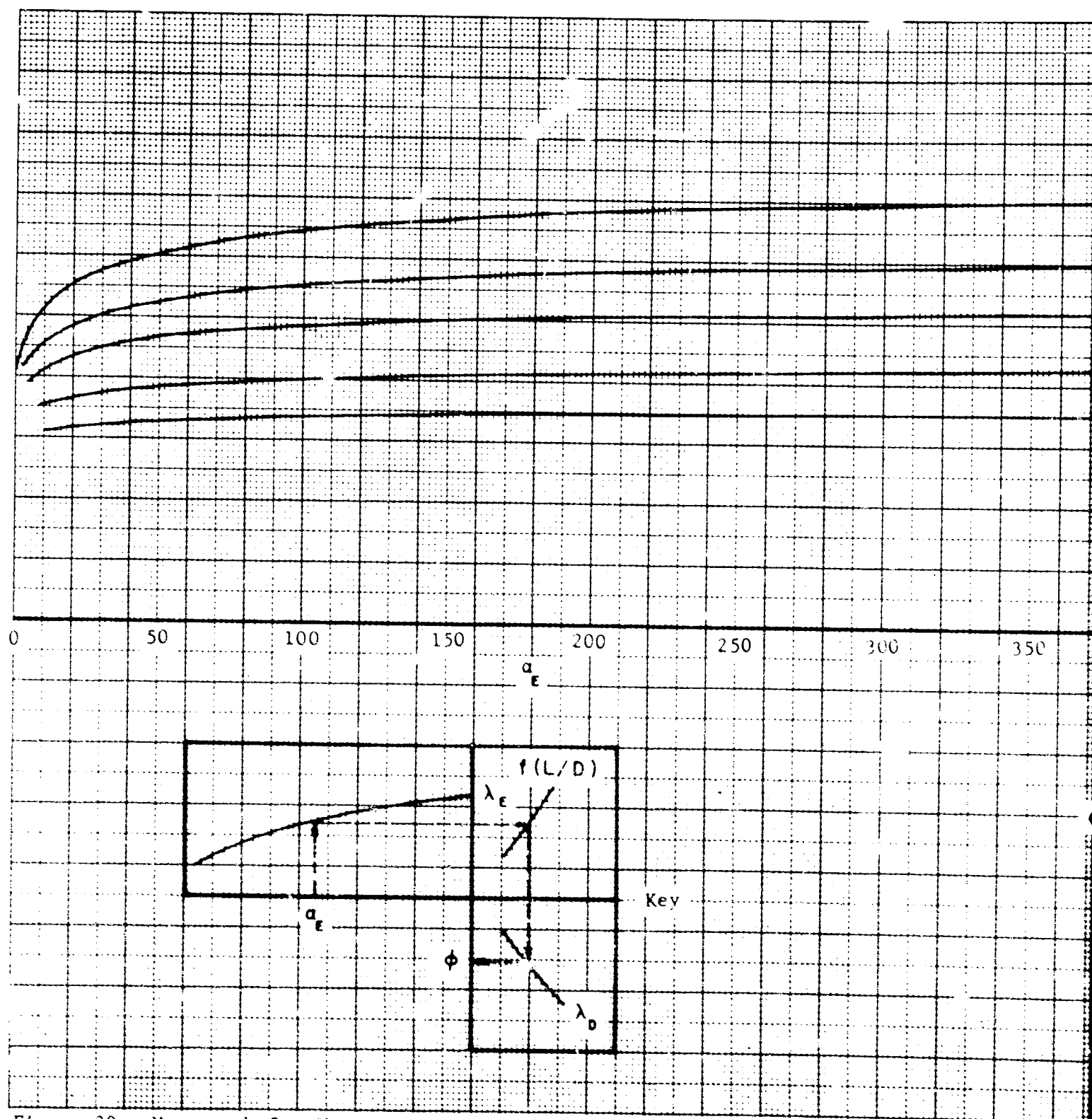
Incompressible

Figure 20. Nomograph for Thrust Augmentation Ratio - Incompressible
Flow Analysis Including Flow Losses ($a_0 = 2.0$; $\mu = 0$)

101

λ_E
0
0.05
0.1
0.2
0.3

f (L/D)
0.05
0.03
0.02
0.01
0

250   300   350

0

φ

1.0

2.0

Key

λ_D
0.4
0.3
0.2
0.1
0

3.0

4.0
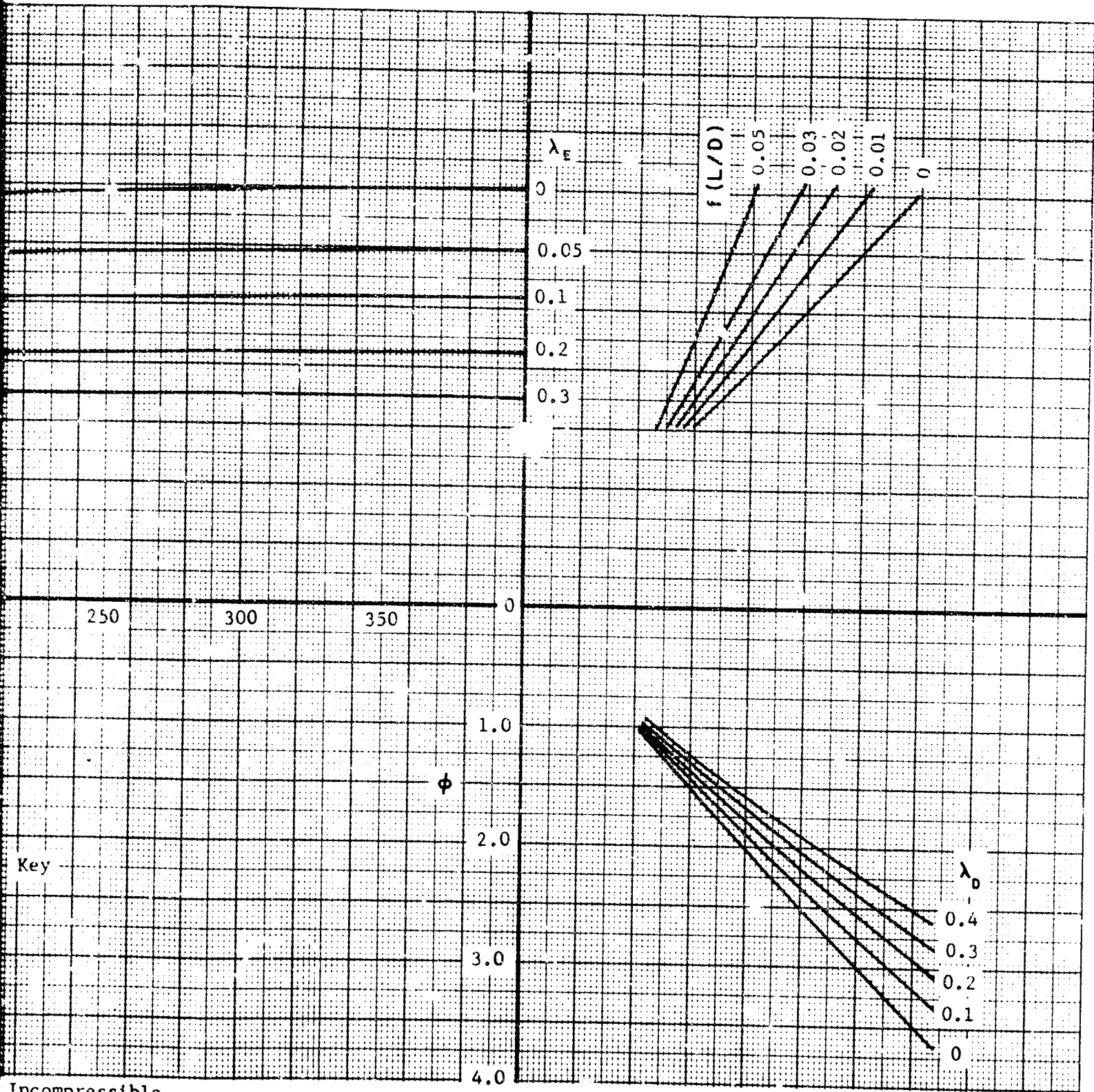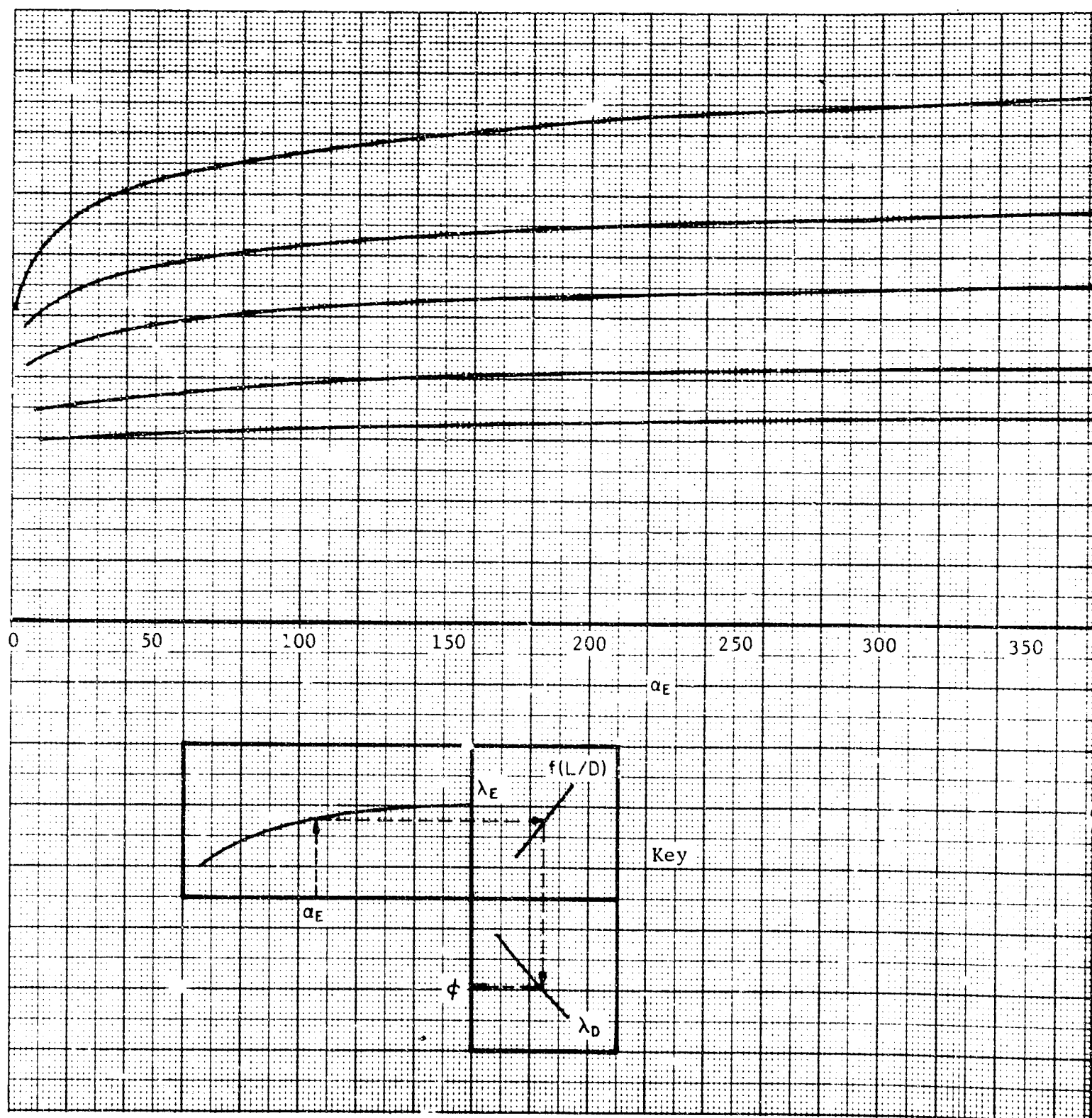
Incompressible

Figure 21. Nomograph for Thrust Augmentation Ratio - Incompressible
Flow Analysis Including Flow Losses ($a_D = 2.5; \mu = 0$)

103
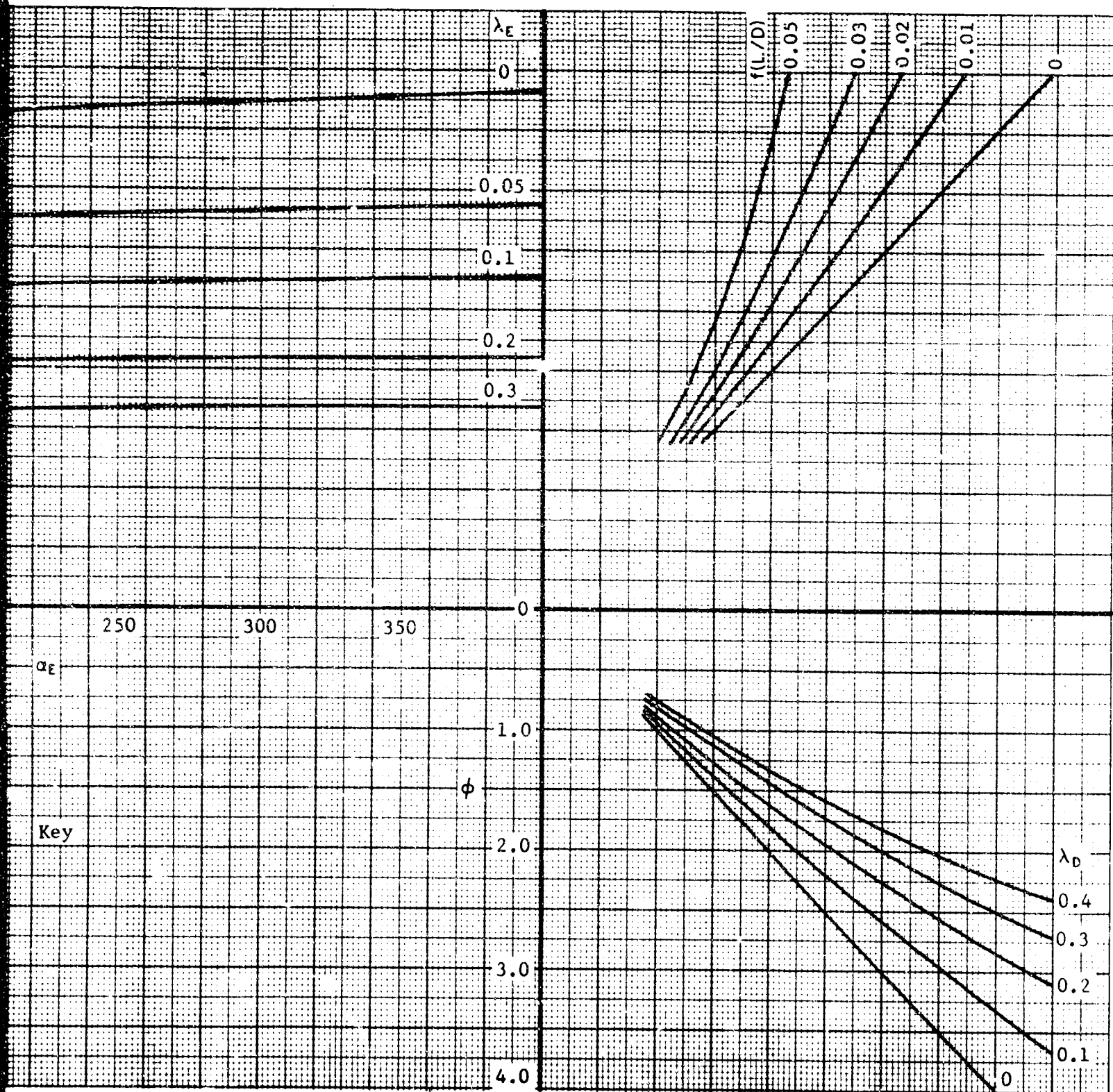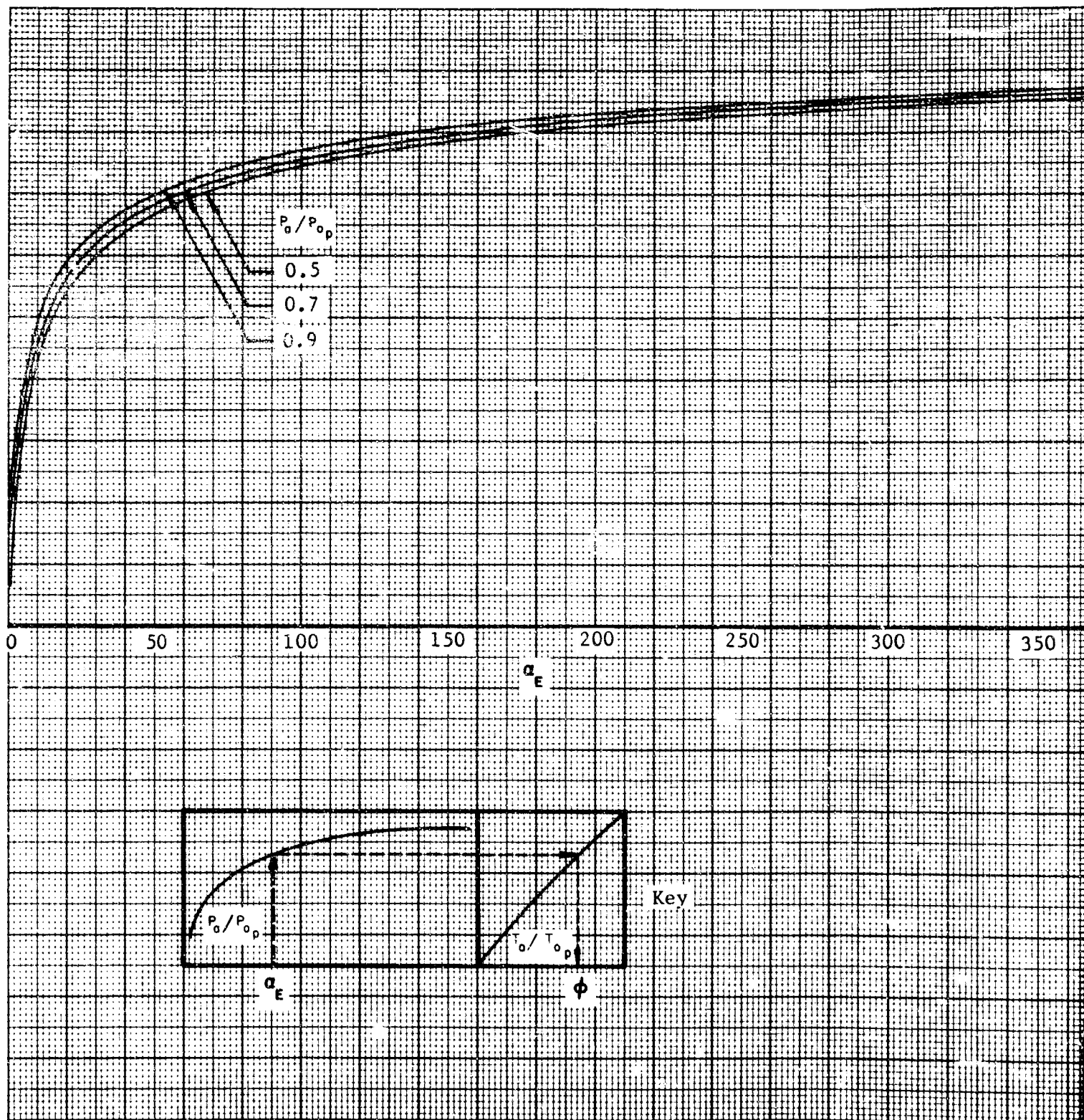
Incompressible

Figure 22. Nomograph for Thrust Augmentation Ratio - Compressible
Flow Analysis Neglecting Flow Losses $(\alpha_D = 1.0; \mu = 0)$

τ_a/τ_{n_p}
0.2
0.3
0.4
0.5
0.7
1.0

250   300   350   1.0   1.2   1.4   1.6   1.8   2.0

ϕ

key
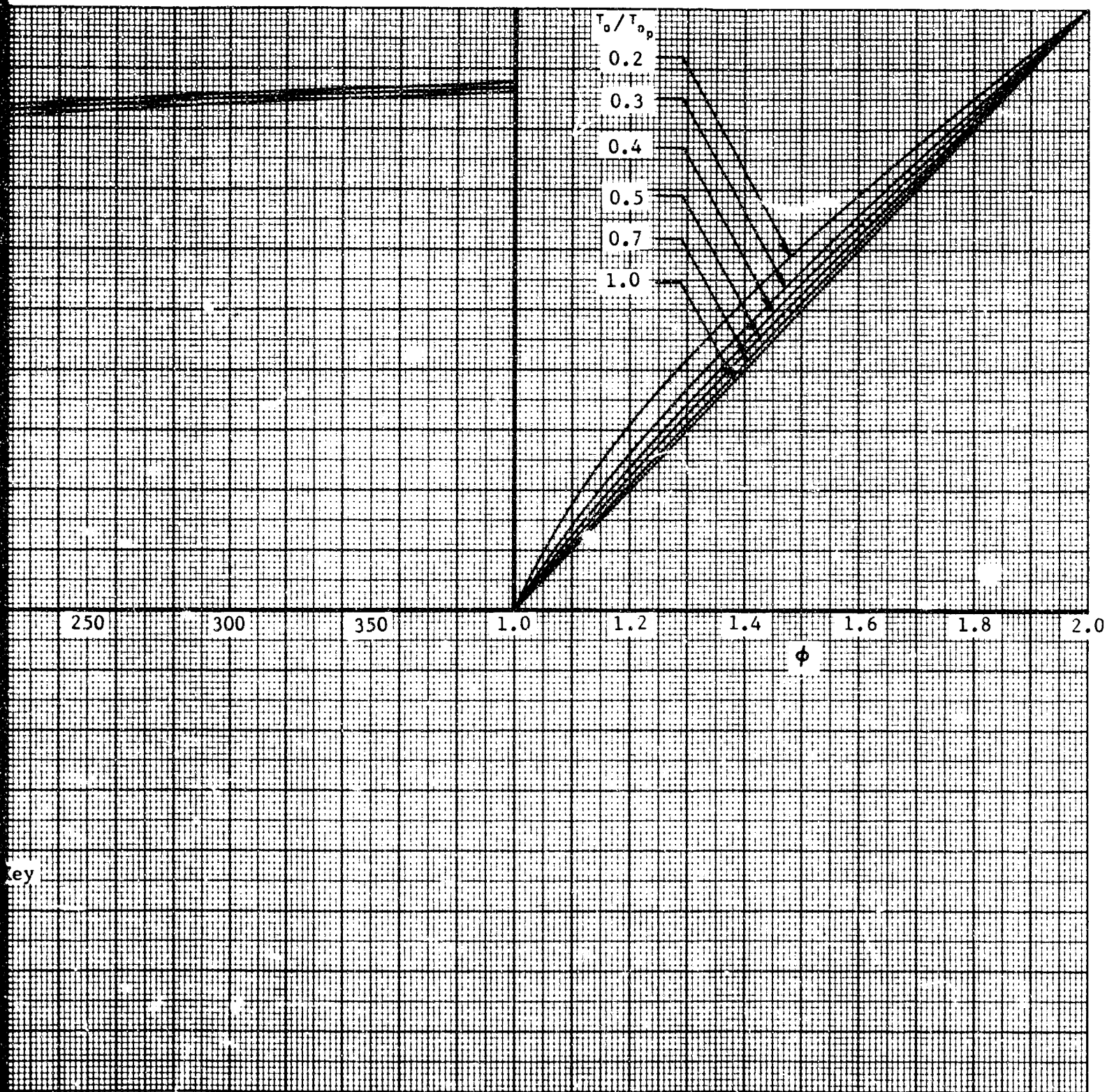
ompressible

A   B

incompressible analysis (including flow losses) for the diffuser area ratios $\alpha_D = 1.0$, 1.5, 2.0, and 2.5, respectively. The fifth nomograph, Figure 22, presents the computer results for the compressible analysis for a wide range of the nondimensionalized input parameters P_a/P_{Op} and T_a/T_{Op}

1. Evaluation of Flow Losses

In utilizing the nomographs for the incompressible analysis, the values of the various loss factors must be predetermined. No precise information is available on these loss factors which are dependent on the design and construction details of the system. However, the following will serve as a general guide:

a. Friction Loss Factor f(L/D)

The friction loss factor of a given jet ejector configuration is a function of the friction factor f along the ejector walls and the mixing chamber length-to-diameter ratio L/D required for complete flow mixing.

The friction factor $f = 0.003$, which is commonly used for commercially smooth pipes is recommended to be used for fairly smooth mixing chamber walls of jet ejectors.

No precise information is available for estimating the mixing chamber length-to-diameter ratios required for complete mixing. However, in order to provide the designer some basis for selection of the required L/D ratios, a semiempirical approach is herein utilized for estimating this parameter. This approach is based on the assumption that for a single nozzle jet ejector the flow losses due to partial mixing can be neglected provided that the mixing chamber length-to-diameter ratio is not less than 6.0. This implies that the flow mixing is considered to be complete for $L/D \geq 6.0$.

The results thus obtained are presented in
Figure 23. This figure can be utilized to
estimate the total mixing chamber length required
for complete flow mixing for single, multiple
(four evenly spaced nozzles), and annular jet
ejector configurations.

Thus, utilizing the friction factor of $f = 0.003$
and the L/D ratios from Figure 23, the required
friction loss factor $f(L/D)$ for any given jet
ejector configuration can be determined.

b. Diffuser Loss Factor λ_D

The diffuser loss factor λ_D is a function of a
total head loss within the diffuser, the dynamic
pressure at the diffuser entrance and its exit-to-
entrance area ratio. A mathematical definition of
this factor is presented in the list of symbols.
Some usable data for determining the loss factor
of various diffuser configurations is presented in
Reference 26.

c. Secondary Entrance Loss Factor λ_E

Very limited information is available for
determining the loss factor at the secondary
entrance. This factor is mainly a function of the
size and shape of the inlet, but it also depends on
the blockage effect of the components of the
ejector, such as manifolds, instrumentation, etc.,
located in the passage of the secondary flow
entrance. It is not possible to determine this
factor accurately, since it varies from case to
case. In Reference 27, representative values of
"internal inlet" loss factor, i.e., for static
conditions with no obstruction of the passage, are
presented as follows:

108
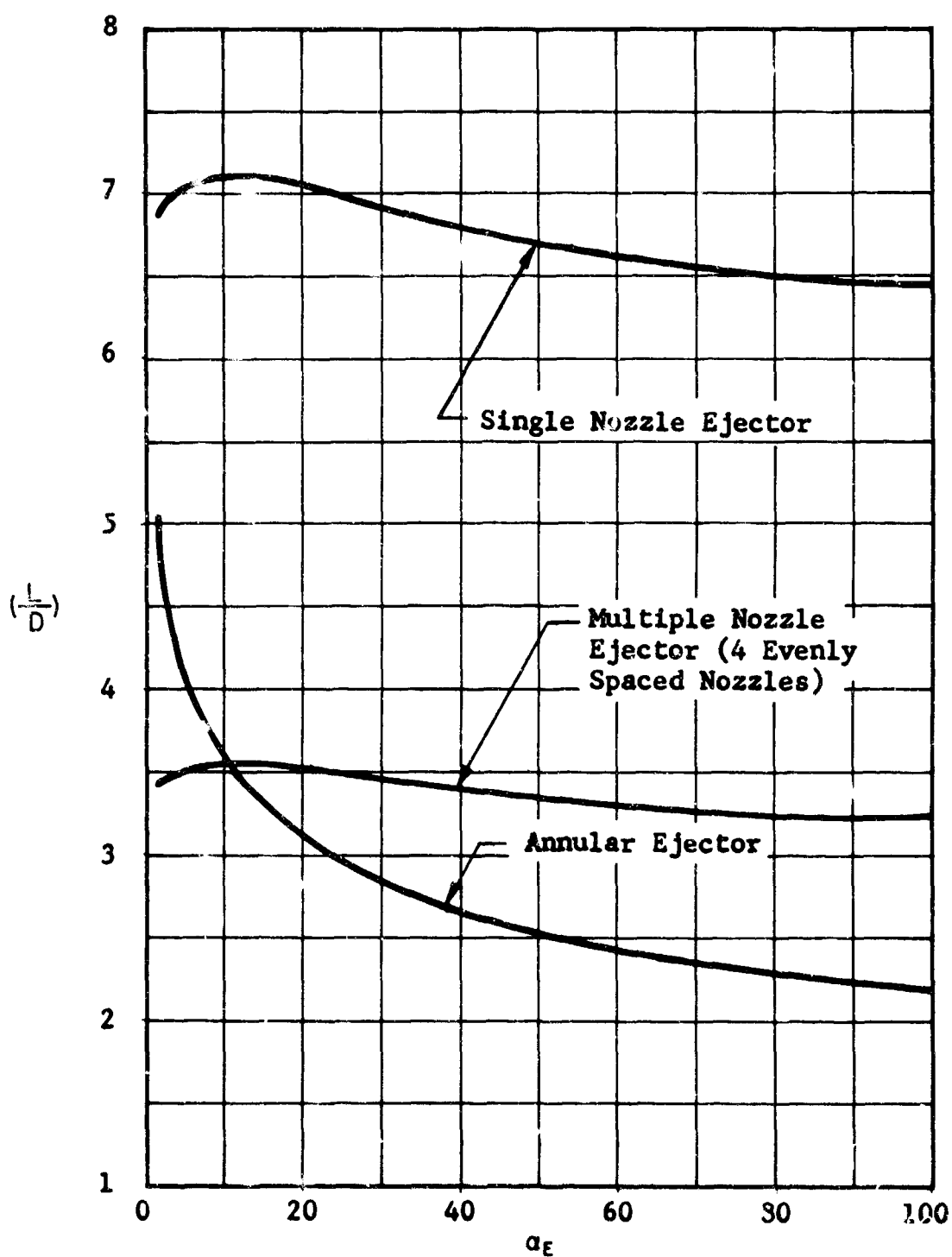
Figure 23. Variation of Minimum Mixing Chamber
Lengths Required for Complete Mixing for Various
Ejector Configurations (Idealized Analysis).

109

Type of Entrance	λ_E
Flared	
Lemniscate contour	0.02
Circular contour	0.03
Straight contour	0.05
Rounded Edge	0.1
Sharp Edge	0.3

It can be noted from the above data that lemniscate lip contour is preferable in ejector designs. This contour tends to minimize adverse pressure gradient over the lip and thus results in lower entrance loss factor. Furthermore, in evaluating the entrance loss factor, a consideration must be given to the ratio of the entrance diameter to the mixing tube diameter. If this ratio is less than 1.5, an additional loss in thrust augmentation ratio may occur. This loss may be accounted for by appropriately increasing the entrance loss factor

2. Correction Factor for the Nonuniform Velocity Profile at the Secondary Entrance

Section IV contains an empirical analysis for determining the effect of a nonuniform velocity profile at the secondary entrance on jet ejector thrust augmentation. This analysis requires a knowledge of the flow nonuniformity parameter κ which can only be reliably predicted from appropriate experimental data.

The limited experimental data such as presented in Table II of Section VI indicates that the approximate value of this parameter is about $\kappa = 70$. Thus, using Figure 3, the empirical correction factor χ for thrust augmentation ratio due to nonuniform velocity profile at the secondary entrance can be determined as follows:

110

$$\chi = \frac{\phi_{\kappa=70}}{\phi_I} \qquad (150)$$

where $\phi_\kappa = 70$ is the thrust augmentation ratio with non-uniform secondary velocity profile for $\kappa = 70$, and ϕ_I is the ideal thrust augmentation ratio for the same α_E .

3. Compressibility Correction Factor C_C

The compressibility correction factor C_C can be obtained as the ratio of the compressible to the ideal value of thrust augmentation ratio ϕ for the same values of α_E and α_D . Thus:

$$C_C = \frac{\phi_C}{\phi_I} \qquad (151)$$

The compressible value of thrust augmentation ratio ϕ_C can be obtained from the nomograph, Figure 22, for a given set of input conditions of P_a/P_{op} and T_a/T_{op}. The corresponding ideal value ϕ_I can be obtained from the nomograph, Figure 18, using $\lambda_E = f(L/D) = 0$.

4. Net Value of Thrust Augmentation Ratio

The net value of thrust augmentation ratio of a given ejector configuration can be expressed as follows:

$$\phi = \chi\, C_C\, \phi_L \qquad (152)$$

where ϕ_L represents the incompressible value of thrust augmentation ratio including the effects of major flow losses. This value can be obtained from appropriate nomographs, Figures 18 to 21. Thus equation (152) can be used to predict the total thrust augmentation ratio of a given

ejector configuration including the effects of nonuniform
entrance velocity, flow compressibility, and major flow
losses discussed above.

5. Use of the Nomographs

The procedure for determining ejector thrust augmentation
performance requires the use of the nomographs presented in
Figures 18 to 22. In order to utilize these charts, it is
first necessary to determine ejector geometry, major flow
losses, and operating conditions of a given jet ejector
configuration. The use of the nomograph is explained
graphically in the key of each chart.

The procedure for the use of nomographs for a general case
of an ejector with a diffuser is as follows:

(a) Select an appropriate nomograph for a given
diffuser exit-to-entrance area ratio λ_D.

(b) On the upper left-hand plot of the nomograph,
draw a vertical line at a given α_E to intersect
with the curve corresponding to the computed
value of entrance loss factor λ_E. Interpolate
between λ_E curves if required.

(c) From the point of intersection of step (b),
project a horizontal line to intersect with the
curve corresponding to the computed value of the
friction loss factor $f(L/D)$. Interpolate between
$f(L/D)$ curves if required.

(d) From the point of intersection of step (c), draw a
vertical line to intersect the curve corresponding
to the computed value of the diffuser loss factor
λ_D. Interpolate between λ_D curves if required.

(e) From the point of intersection of step (d), draw
a horizontal line to intersect with the scale of
the thrust augmentation ratio. Read off this
value of thrust augmentation ratio ϕ_L, which in
this case would correspond to the incompressible
value including the flow losses and the effect of
a diffuser.

112

Similar procedure is applied in the use of the nomograph
for an ejector without diffuser (Figure 18), except that the
vertical line of step (d) is drawn to intersect the
horizontal scale of thrust augmentation ratio. The point of
intersection of the vertical line with the scale yields the
required value of ϕ_L with no diffuser.

The procedure for the use of the nomograph (Figure 22) to
determine the compressible value of thrust augmentation
ratio is similar to that described above. However, in this
case the nomograph is entered using the precomputed values
of ambient-to-stagnation pressure and temperature ratios,
P_a/P_{op} and T_a/T_{op} respectively.

In the cases where the ejector performance is required for
some intermediate values of diffuser area ratios a_D, the
usual interpolation procedures between the nomographs can be
utilized.

6. Limitations of the Nomographs

Although the nomographs (Figures 18 to 22) represent a rapid
and a practical analytical tool in evaluating performance
of a given jet ejector configuration, the usefulness of the
charts is limited by the assumptions inherent in the
analysis.

The major problem exists in the user's ability to accurately
predetermine the required flow losses of a given ejector
configuration.

The assumptions used to determine the friction factor along
the mixing chamber walls ($f = 0.003$), the total mixing chamber
length for complete mixing, and the flow nonuniformity
parameter ($\kappa = 70$) for the velocity profile at the secondary
entrance require further experimental verification

The nomographs have been carefully prepared and their
accuracy is expected to be within ± 3 percent of the
computer results.

113

C. PROCEDURE FOR DETERMINING PERFORMANCE OF A GIVEN JET EJECTOR CONFIGURATION

The following procedure can be utilized to determine the performance of a given jet ejector configuration:

(i) Determine the following geometric parameters and operation conditions:

(a) Type of ejector configuration

(b) Number of primary nozzles, N

(c) Secondary-to-primary area ratio, α_E

(d) Diffuser exit-to-entrance area ratio, α_D

(e) Diffuser length and expansion angle

(f) Mixing chamber shape

(g) Ejector intake geometry

(h) Ejector operating conditions, P_a/P_{o_p} and T_a/T_{o_p}

(ii) Knowing α_E and the type of ejector configuration, enter Figure 23 and obtain the total mixing chamber length (L/D) required for complete mixing. For the case of a multiple nozzle ejector configuration with N ≠ 4.0, determine the total mixing chamber length using the following equation:

$$\left(\frac{L}{D}\right)_M = \frac{1}{\sqrt{N}}\left(\frac{L}{D}\right)_S \qquad (153)$$

where $(L/D)_S$ can be obtained from Figure 23.

114

(iii)   Assuming friction factor $f = 0.003$, compute
        ejector friction loss factor $f(L/D)$ using
        (L/D) value from step (ii).

(iv)   Using data of Reference 26 (or other pertinent
        data) and the diffuser geometry from step (i),
        determine diffuser loss factor λ_D .

(v)   Using data of Reference 27 (or other pertinent
        data) and ejector intake geometry from step (i),
        determine the ejector entrance loss factor λ_E .

(vi)   With the flow losses determined in steps (iii) to
        (v) and known values of α_E and α_D from step (i),
        enter the appropriate nomograph and obtain the
        incompressible value of thrust augmentation ratio
        including flow losses, ϕ_L .

(vii)   Using α_E from step (i) an' assuming $\kappa = 70$, enter
        Figure 3 and obtain $\phi_{\kappa=70}$ and ϕ_I . Then
        compute the empirical correction factor χ from
        equation (150). This factor accounts for the
        reduction of thrust augmentation ratio due to
        nonuniform velocity profile at the secondary
        entrance.

(viii) Using the operation conditio. of P_0/F_{op} and $\overline{}^{,-}_{op}$
        and α_E from step (i), enter nomograph Figure 22
        and determine the compressible value of thrust
        augmentation ratio ϕ_C . Also, enter Figure 18
        using $\lambda_E = f(L/D) = 0$ and obtain ideal value of
        thrust augmentation ratio ϕ_I . Then compute the
        compressibility correction factor C_C using
        equation (151).

(ix)   Using ϕ_L from step (vi), χ from step (vii), and
        C_C from step (viii), compute the required thrust
        augmentation ratio from equation (152).

(x)   For a known mixing chamber shape, compute mass
        entrainment ratio w using equation (34) for
        const nt area mixing or equation (51) for constant

pressure mixing. The mass entrainment ratio for compressible analysis or incompressible analysis including major flow losses can be most conveniently obtained using the computer program described in Appendix I.

D. SAMPLE CALCULATION

To more clearly indicate the analytical procedures for determining ejector performance, a sample calculation is performed as follows:

(i) Assume a single, central nozzle configuration of constant area mixing chamber having $\alpha_E = 100$ and $\alpha_D = 2.0$. Also assume the following operation conditions $T_a = 70°F$, $T_{op} = 600°F$, $P_a = 14.7$ lb/in^2, and $P_{op} = 21$ lb/in^2.

Compute

$$\frac{T_a}{T_{op}} = \frac{70+460}{600+460} = \frac{530}{1060} = 0.5$$

$$\frac{P_a}{P_{op}} = \frac{14.7}{21.0} = 0.7$$

(ii) Using $\alpha_E = 100$, enter Figure 23 and obtain

$$(\frac{1}{D})_s = 6.43$$

(iii) Assuming friction factor $f = 0.003$, calculate ejector friction loss factor using $(L/D) = 6.43$ from step (ii). Thus,

$$f(L/D) = 0.003 \times 6.43 = 0.0193$$

116

(iv) Using data of Reference 26, determine the
      diffuser loss factor

$$\lambda_D = 0.2$$

(v)   Using data of Reference 27, determine entrance
      loss factor

$$\lambda_E = 0.1$$

(vi) With the flow losses computed in steps (iii) to
      (v) and using $\alpha_E = 100$, $\alpha_D = 2.0$, enter
      nomograph Figure 20 and determine the incompressible
      value of thrust augmentation ratio including flow
      losses

$$\phi_L = 1.98$$

(vii) Assuming $\kappa = 70$ and using $\alpha_E = 100$, enter
      Figure 3 and obtain

$$\phi_{\kappa=70} = 1.745$$

$$\phi_I = 1.776$$

      Compute the empirical correction factor χ for
      thrust augmentation ratio due to nonuniform
      velocity profile at the secondary entrance; thus,

117

$$\chi = \frac{\phi_{K=70}}{\phi_I} = \frac{1.745}{1.776} = 0.983$$

(viii)   Using the values $P_a/P_{0p} = 0.7$ and $T_0/T_{0p} = 0.5$ computed in step (i), enter nomograph Figure 22 and obtain the compressible value of thrust augmentation ratio corresponding to $\alpha_E = 100$. Thus,

$$\phi_C = 1.737$$

Also enter nomograph Figure 18 using $\lambda_E = f(L/D) = 0$ and $\alpha_E = 100$ and determine ideal value of thrust augmentation ratio. Thus,

$$\phi_I = 1.776$$

Compute compressibility correction factor

$$C_C = \frac{\phi_C}{\phi_I} = \frac{1.737}{1.776} = 0.978$$

(ix)   Finally, using $\phi_L = 1.98$ (from step (vii), $\chi = 0.983$ (from step (vii)), and $C_C = 0.978$ (from step viii), compute the required thrust augmentation ratio as follows:

$$\phi = \phi_L \chi C_C = 1.98 \times 0.983 \times 0.978 = 1.90$$

(x) Using $\alpha_E = 100$ and $\alpha_D = 2.0$, compute mass entrainment ratio w from equation (34); thus,

$$w = \frac{(\alpha_E + 1)\alpha_D \left[-(\alpha_E - 1)\alpha_D + \alpha_E \sqrt{\alpha_D^2 + 2\alpha_E - 1} \right] - (\alpha_E^2 + \alpha_D^2)}{\alpha_E^2 + \alpha_D^2}$$

$$w = \frac{(100 + 1)2 \left[(100 - 1)2 + 100 \sqrt{2^2 + 2 \times 100 - 1} \right] - (100^2 + 2^2)}{100^2 + 2^2}$$

$$= \frac{202 \left[-198 + 100 \sqrt{103} \right] - 10004}{10004} = 15.49$$

119

VIII.   CONCLUSIONS AND RECOMMENDATIONS

1. A review of the technical literature shows that the
    existing analytical and experimental information on
    the thrust augmentation characteristics of jet ejectors
    cannot be used as an effective design tool.

2. The analysis performed in this report indicates that a
    constant area mixing ejector yields a higher thrust
    augmentation ratio than an equivalent constant pressure
    mixing configuration.

3. For any practical value of secondary-to-primary area
    ratio, the thrust augmentation ratio reaches an optimum
    value with the diffuser area ratio ranging between 1.5
    and 2.0.

4. To obtain a maximum thrust augmentation, the mixing
    chamber length should be compromised so as to achieve
    the best mixing with a minimum wall friction.

5. Annular and multiple nozzle ejectors require
    substantially shorter mixing chamber lengths for complete
    mixing as compared to an equivalent single, central
    nozzle configuration.

6. The flow losses have a predominant effect on jet ejector
    performance, whereas flow compressibility is only of
    secondary importance.

7. An increase of forward speed (parallel or perpendicular
    to the ejector) causes a decrease of the thrust
    augmentation ratio.

8. The available test data are insufficient to determine
    reliably the validity of the assumptions utilized in
    the analyses. It is therefore recommended that a
    systematic test program be conducted to determine the
    applicability of these assumptions as well as to
    provide more precise information to evaluate the
    empirical correction factors presented in this report.

IX. REFERENCES

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APPENDIX I

COMPUTER PROGRAMS FOR SOLUTION OF FLOW EQUATIONS FOR THE PRACTICAL ANALYSIS

Due to the complexity of the flow equations which require
tedious and lengthy computation, it was decided that a more
efficient and accurate method of obtaining the required
results would be by the use of a digital computer. The
practical analysis presented in Section IV was therefore
programmed on an IBM 360 computer utilizing BPS FORTRAN IV
language. Two separate prog....ms were performed. The first
program deals with the incompressible flow analysis whereby
major flow losses and the effect of a diffuser and forward
speed are included. The second program deals exclusively
with flow compressibility.

1. Incompressible Flow Analysis

As mentioned previously, the effect of the major flow losses,
diffuser, and forward speed are investigated on the basis of
the incompressible flow analysis. This is accomplished by
solving equation (57) for the velocity ratio V_3/V_{1p}. The
velocity ratio V_{1s}/V_{1p} is then computed from equation (58).
The thrust augmentation ratio ϕ and mass entrainment ratio w
are obtained from equations (60) and (62), respectively. A
simplified flow diagram of this program is presented in
Figure 24, and a typical IBM computer output is shown in
Table XIV.

2. Compressible Flow Analysis

The compressible flow analysis as presented in Section IV
involves a simultaneous solution of the two nonlinear
equations (85) and (86) for the two unknowns V_2/V_{op} and
T_{1p}/T_{op} in terms of given input parameters P_a/P_{op}, T_a/T_{op},
and α_E. However, in generating the required computer data,
equations (85) and (86) are solved in their equivalent
dimensional form as follows:

125
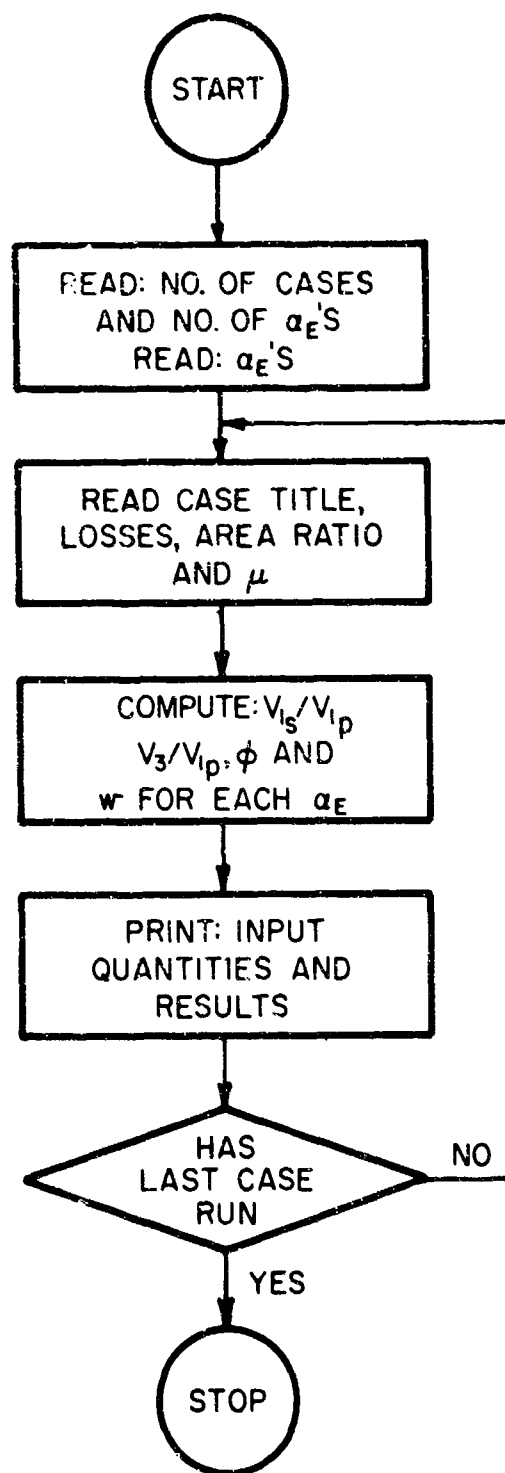
Figure 24. Computer Flow Diagram for Incompressible Analysis.

TABLE XIV

TYPICAL COMPUTER RESULTS FOR INCOMPRESSIBLE ANALYSIS

CASE 1
DIFFUSER AREA RATIO= 0.20000E 01   LAMBDA-E= 0.10000E 00
FRICTION FACTOR= 0.10000E-01   LAMBDA-D= 0.20000E 00
VINF/VAP= 0.50000E-01   NO. OF ALPHAS= 10

	ALPHA	PHI	ENT RATIO	VIS/V1P	V3/V1P
1	0.10000E 00	0.14974E 01	0.76892E-01	0.76892E 00	0.48950E 00
2	0.10000E 01	0.14544E 01	0.69139E 00	8.69139E 00	0.42285E 00
3	0.50000E 01	0.14451E 01	0.26513E 01	0.53025E 00	0.30427E 00
4	0.10000E 02	0.14440E 01	0.44154E 01	0.44154E 00	0.24616E 00
5	0.50000E 02	0.13434E 01	0.12799E 02	0.25599E 00	0.13529E 00
6	0.10000E 03	0.12168E 01	0.19770E 02	0.19770E 00	0.10282E 00
7	0.25000E 03	0.93104E 00	0.35666E 02	0.14266E 00	0.73036E-01
8	0.50000E 03	0.58071E 00	0.57732E 02	0.11546E 00	0.58615E-01
9	0.10000E 04	0.14832E-01	0.97985E 02	0.97985E-01	0.49443E-01
10	0.50000E 04	-0.38282E 01	0.40217E 03	0.80435E-01	0.40309E-01

$$\frac{\rho_{lp}}{g}\left\{\sqrt{2\,g\,c_p T_{op} J\left[1-\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op} J}{P_{op}}\right)^{\gamma-1}\right]}+\right.$$

$$\left.\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{op}}{T_a}\right)\sqrt{2\,g\,c_p T_a J\left[1-\left(\frac{P_{op}}{P_a}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op} J}{P_{op}}\right)^{\gamma-1}\right]}\right\}V_2+$$

$$(\alpha_E+1)P_a-\rho_{lp}c_p T_{op} J\left[(\alpha_E+1)\frac{\gamma-1}{\gamma}\left(\frac{\rho_{lp}c_p T_{op} J}{P_{op}}\right)^{\gamma-1}-2-2\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\right]=0$$

$$\dots(154)$$

$$\frac{\rho_{lp}}{2g}\left\{\sqrt{2\,g\,c_p T_{op} J\left[1-\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op} J}{P_{op}}\right)^{\gamma-1}\right]}+\right.$$

$$\left.\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{T_{op}}{T_a}\right)\sqrt{2\,g\,c_p T_a J\left[1-\left(\frac{P_{op}}{P_a}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op} J}{P_{op}}\right)^{\gamma-1}\right]}\right\}V_2^2+$$

$$(\alpha_E+1)\frac{\gamma}{\gamma-1}P_a V_2-\rho_{lp}c_p T_{op} J\left\{\sqrt{2\,g\,c_p T_{op} J\left[1-\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op} J}{P_{op}}\right)^{\gamma-1}\right]}+\right.$$

$$\left.\alpha_E\left(\frac{P_a}{P_{op}}\right)^{\frac{\gamma-1}{\gamma}}\sqrt{2\,g\,c_p T_a J\left[1-\left(\frac{P_{op}}{P_a}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{\gamma-1}{\gamma}\cdot\frac{\rho_{lp}c_p T_{op} J}{P_{op}}\right)^{\gamma-1}\right]}\right\}=0$$

$$\dots(155)$$

The two nonlinear equations, (154) and (155), are solved for the two unknowns ρ_{1p} and V_2 in terms of dimensional input values of P_a, P_{0p}, T_a, and T_{0p}. The solution of these two equations, designated as ψ_1 and ψ_2, respectively, is obtained using the Newton-Raphson iteration procedure and Taylor's series as follows:

$$(\rho_{1p})_{i+1} = (\rho_{1p})_i + (h)_i \tag{156}$$

$$(V_2)_{i+1} = (V_2)_i + (k)_i \tag{157}$$

where $i = 0, 1, 2 \ldots$ representing successive iterations. Using Taylor's series, the functions $(\psi_1)_{i+1}$ and $(\psi_2)_{i+1}$ can be expressed as follows:

$$(\psi_1)_{i+1} = (\psi_1)_i + (h)_i \left(\frac{\partial \psi_1}{\partial \rho_{1p}}\right)_i + (k)_i \left(\frac{\partial \psi_1}{\partial V_2}\right)_i \tag{158}$$

$$(\psi_2)_{i+1} = (\psi_2)_i + (h)_i \left(\frac{\partial \psi_2}{\partial \rho_{1p}}\right)_i + (k)_i \left(\frac{\partial \psi_2}{\partial V_2}\right)_i \tag{159}$$

Solving for $(h)_i$ and $(k)_i$ from equations (158) and (159) yields

$$(h)_i = \frac{\begin{vmatrix} -\psi_1 & \dfrac{\partial \psi_1}{\partial V_2} \\[2ex] -\psi_2 & \dfrac{\partial \psi_2}{\partial V_2} \end{vmatrix}_i}{\begin{vmatrix} \dfrac{\partial \psi_1}{\partial \rho_{1p}} & \dfrac{\partial \psi_1}{\partial V_2} \\[2ex] \dfrac{\partial \psi_2}{\partial \rho_{1p}} & \dfrac{\partial \psi_2}{\partial V_2} \end{vmatrix}_i} \tag{160}$$

129

$$(k)_i = \cfrac{\begin{vmatrix} \dfrac{\partial \psi_1}{\partial \rho_{1p}} & -\psi_1 \\[2ex] \dfrac{\partial \psi_2}{\partial \rho_{1p}} & -\psi_2 \end{vmatrix}_i}{\begin{vmatrix} \dfrac{\partial \psi_1}{\partial \rho_{1p}} & \dfrac{\partial \psi_1}{\partial V_2} \\[2ex] \dfrac{\partial \psi_2}{\partial \rho_{1p}} & \dfrac{\partial \psi_2}{\partial V_2} \end{vmatrix}_i} \tag{161}$$

The above iteration procedure is started assuming initial conditions $(i = 0)$

$$(\rho_{1p})_0 = K_1 \rho_{ap} \tag{162}$$

$$(V_2)_0 = K_2 V_{ap} \tag{163}$$

where K_1 and K_2 are suitable programmed constants and ρ_{ap} and V_{ap} are obtained from equations (71) and (72), respectively.

A simplified flow diagram of this computer program is shown in Figure 25, and a typical sample of final output is presented in Table XV.

130

START

READ NO OF CASES, NO OF α_E'S, AND ϵ

READ CASE TITLE, $T_a, P_a, T_{op}, P_{op}, V_a, C_p$ AND γ

COMPUTE: ρ_{op}, T_{op} AND V_{op}

ITERATE FOR ρ_{1p} AND V_2 IN SUBROUTINE NEWTON

COMPUTE ρ_2, T_2, M_2, V_{1s} AND V_{1p}

COMPUTE $\rho_3, P_1, T_{1s}, T_{1p}, M_{1s}, M_{1p}$

ENTER

COMPUTE ρ_{1p_0}, V_{2_0}

COMPUTE $\dfrac{\partial \psi_1}{\partial \rho_{1p}}, \dfrac{\partial \psi_2}{\partial \rho_{1p}}, \dfrac{\partial \psi_1}{\partial V_2}, \dfrac{\partial \psi_2}{\partial V_2}$

IS $\dfrac{\partial \psi_1}{\partial \rho_{1p}} \cdot \dfrac{\partial \psi_2}{\partial V_2} = \dfrac{\partial \psi_2}{\partial \rho_{1p}} \cdot \dfrac{\partial \psi_1}{\partial V_2}$

YES

$(V_2)_{i+1} = 0.8(V_2)_i$

NO

COMPUTE: h,k

I CHECK = O

IS $(\rho_{1p})_i + h \geq \rho_{op}$

YES

$(\rho_{1p})_{i+1} = \dfrac{(\rho_{1p})_i + \rho_{op}}{2}$

NO
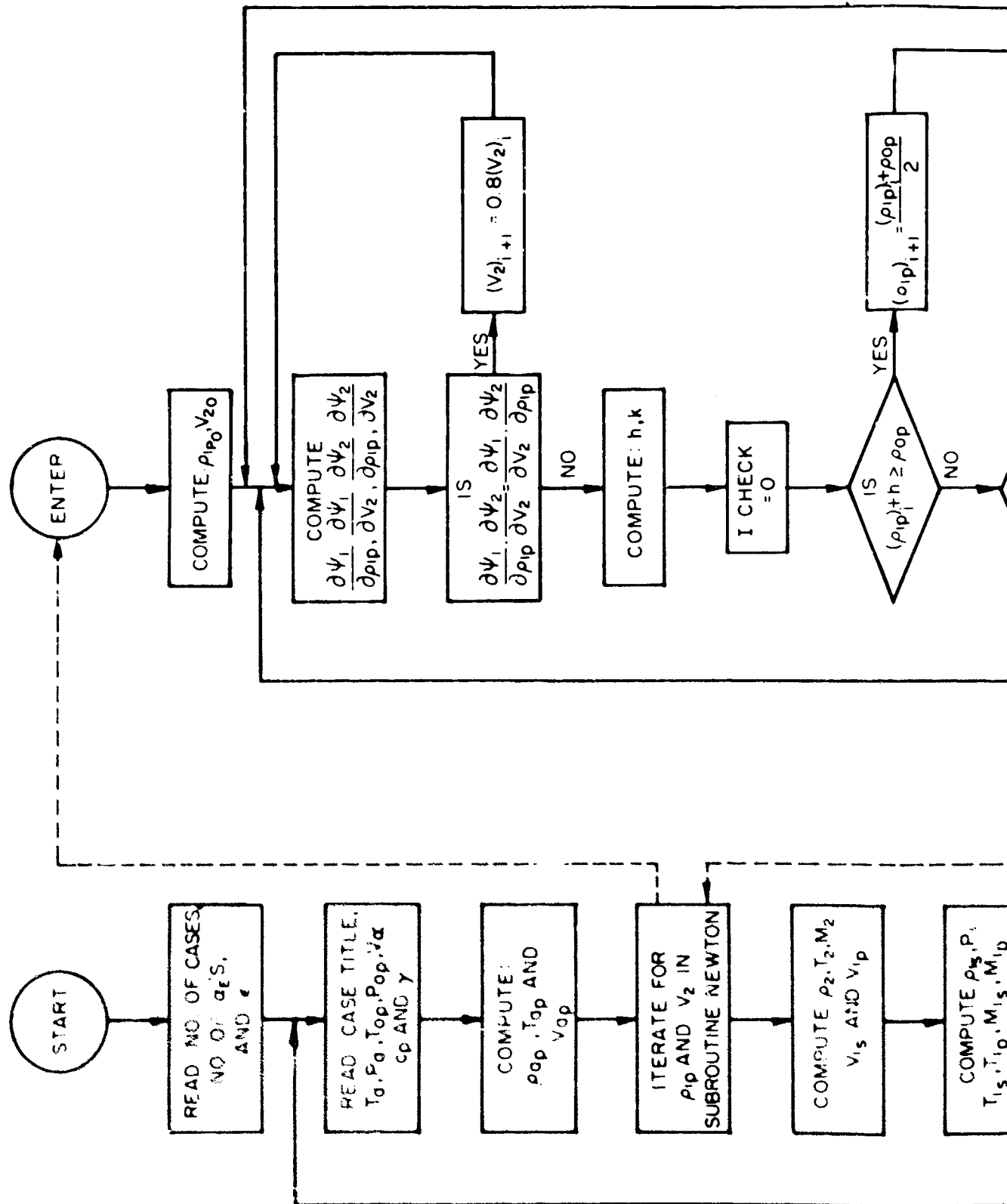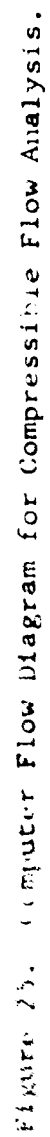
Figure 25. Computer Flow Diagram for Compressible Flow Analysis.

TABLE XV

TYPICAL COMPUTER RESULTS FOR COMPRESSIBLE ANALYSIS

AIR TEMP	STAG TEMP	V-INF	GAMMA	SPEC HEAT
0.53000E 03	0.10600E 04	0.0	0.14000E 01	0.24100E 00

AMB PRESSURE 0.2 7C0E 04
TOTAL PRESSURE 0.36000E 04

PRIMARY JET TO AMBIENT
RHO(AP)= 0. 98E-01   T(AP)= 0.9108CE 03   V(AP)= 0.13422E 04   MACH NO.= 0.9050E 00

PRIMARY JET IN MIXING CHAMBER

ALPHA	DENSITY	PRESSURE	TEMPERATURE	VELOCITY	MACH NO.
0.50000E-02	0.42733E-01	0.20724E 04	0.905285E 03	0.13568I E 04	0.92441E 00
0.10000E-01	0.42280E-01	0.20382IE 04	0.9009892E 03	0.13856SF 04	0.91337AE 00
0.50000E-01	0.39672E-01	0.18676CE 04	0.8787691E 03	0.16793IE 04	0.10154E 01
0.10000E 00	0.384C E-01	0.17856SE 04	0.8667571E 03	0.15243ZE 04	0.10510E 01
0.20000E 00	0.38037E-01	0.17607EE 04	0.8441101E 03	0.15380CE 04	0.10546EE 01
0.50000E 00	0.38551 E-01	0.17811EE 04	0.8569443E 03	0.15269IE 04	0.10552CE 01
0.10000E 01	0.38942E-01	0.18214SE 04	0.8725C5E 03	0.15046SE 04	0.10365TE 01
0.20000E 01	0.39197E-01	0.18773SE 04	0.8708C0CE 03	0.14739TE 04	0.14C10I0E 00
0.50000E 01	0.41043E-01	0.19584TE 04	0.8907746E 03	0.14294TE 04	0.97462E 00
0.10000E 02	0.41831E-01	0.20115TE 04	0.8947610E 03	0.14008CE 04	0.95315E 00
0.50000E 02	0.42914EE-01	0.20847TE 04	0.9068231E 03	0.13696IE 04	0.91961E 00
0.10000E 03	0.43272E-01	0.20989TE 04	0.9085838E 03	0.13552IE 04	0.91282I6E 00

TABLE XV (CONTINUED)

SECONDARY JET IN MIXING CHAMBER

ALPHA	DENSITY	PRESSURE	TEMPERATURE	VELOCITY	MACH NO.
0.50000E-02	0.734369E-01	0.207242E 04	0.526788E 03	0.196959E 03	0.174624E 00
0.10000E-01	0.725688E-01	0.203821E 04	0.524289E 03	0.262618E 03	0.233391E 00
0.50000E-01	0.681766E-01	0.186762E 04	0.511357E 03	0.474458E 03	0.426953E 00
0.10000E 00	0.660256E-01	0.178565E 04	0.504842E 03	0.551145E 03	0.499170E 00
0.20000E 00	0.653676E-01	0.176078E 04	0.502823E 03	0.572858E 03	0.519857E 00
0.50000E 00	0.659063E-01	0.178113E 04	0.504477E 03	0.555156E 03	0.502966E 00
0.10000E 01	0.669685E-01	0.182145E 04	0.507713E 03	0.518763E 03	0.468494E 00
0.20000E 01	0.684302E-01	0.187735E 04	0.512117E 03	0.464690E 03	0.417853E 00
0.50000E 01	0.705293E-01	0.195847E 04	0.518344E 03	0.375167E 03	0.335320E 00
0.10000E 02	0.718902E-01	0.201157E 04	0.522322E 03	0.304506E 03	0.271126E 00
0.50000E 02	0.737490E-01	0.208477E 04	0.527683E 03	0.167302E 03	0.148284E 00
0.10000E 03	0.741076E-01	0.209897E 04	0.528707E 03	0.124968E 03	0.110595E 00

134

TABLE XV (CONTINUED)

MIXED-FLOW AFTER EXIT FROM MIXING CHAMBER (NO DIFFUSER)

ALPHA	DENSITY	TEMPERATURE	VELOCITY	MACH NO.
0.50000E-02	0.434028E-01	0.910489E 03	0.134068E 04	0.904133E 00
0.10000E-01	0.434289E-01	0.909943E 03	0.133834E 04	0.902828E 00
0.50000E-01	0.437573E-01	0.903114E 03	0.131254E 04	0.888762E 00
0.10000E 00	0.442239E-01	0.893584E 03	0.127871E 04	0.870456E 00
0.20000E 00	0.450804E-01	0.876607E 03	0.121988E 04	0.838415E 00
0.50000E 00	0.472450E-01	0.836443E 03	0.108440E 04	0.762985E 00
0.10000E 01	0.499867E-01	0.790566E 03	0.934007E 03	0.675967E 00
0.20000E 01	0.536516E-01	0.736563E 03	0.759784E 03	0.569678E 00
0.50000E 01	0.590884E-01	0.668791E 03	0.538652E 03	0.423845E 00
0.10000E 02	0.628716E-01	0.628547E 03	0.401234E 03	0.325666E 00
0.50000E 02	0.689797E-01	0.572890E 03	0.191952E 03	0.163193E 00
0.10000E 03	0.705888E-01	0.559831E 03	0.138077E 03	0.118751E 00

135

TABLE XV (CONCLUDED)

ALPHA	PHI	ENT. RATIO	NO OF ITERATIONS
0.50000E-02	0.100307E 01	0.123819E-02	2
0.10000E-01	0.100515E 01	0.325701E-02	2
0.50000E-01	0.101265E 01	0.275586E-01	5
0.10000E 00	0.101762E 01	0.621375E-01	5
0.20000E 00	0.102991E 01	0.128017E 00	5
0.50000E 00	0.106616E 01	0.312428E 00	5
0.10000E 01	0.111579E 01	0.592491E 00	4
0.20000E 01	0.118872E 01	0.108356E 01	4
0.50000E 01	0.131603E 01	0.225511E 01	4
0.10000E 02	0.142442E 01	0.373700E 01	3
0.50000E 02	0.165834E 01	0.105701E 02	3
0.10000E 03	0.173899E 01	0.158825E 02	5

APPENDIX II

BIBLIOGRAPHY

Presented in this Appendix is a compilation of a total of 585 technical reports on the state of the art of jet ejectors. For convenience, the papers are arranged in an alphabetical order by authors. A portion of the technical reports presented herein are discussed in Section III of this report. The following constitutes a fairly complete bibliography on jet ejectors:

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138

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146

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163

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165

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166

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172

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179

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180

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181

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183

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13. ABSTRACT

Presented in this investigation is a theoretical analysis of
the thrust augmentation characteristics of jet ejectors. The
analysis includes the effects of flow compressibility, major
flow losses, and forward speed. Numerical results are presented
in the form of nomographs for a wide range of practical
operating conditions. These computations were performed with
the aid of an IBM digital computer. The charts can be used to
predict the jet ejector performance and as such represent an
effective analytical tool for preliminary design purposes.
The numerical results are used to determine the effects of
the more important aerodynamic, thermodynamic, and geometric
parameters on jet ejector thrust augmentation. A correlation
of these results with the available experimental data is also
made.

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